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ELECTRIC VEHICLE BATTERY SIMULATION: HOW ELECTRODE POROSITY AND THICKNESS IMPACT COST AND PERFORMANCE

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ABSTRACT

Lithium-ion batteries almost exclusively power today's electric vehicles (EVs). Cutting battery costs is crucial to the promotion of EVs. This paper aims to develop potential solutions to lower the cost and improve battery performance by investigating its design variables: positive electrode porosity and thickness. The open-access lithium-ion battery design and cost model (BatPac) from the Argonne National Laboratory of the United States Department of Energy, has been used for the analyses. Six pouch battery systems with different positive materials are compared in this study (LMO, LFP, NMC 532/LMO, NMC 622, NMC 811, and NCA). Despite their higher positive active material price, nickel-rich batteries (NMC 622, NMC 811, and NCA) present a cheaper total pack cost per kilowatt-hour than other batteries. The higher thickness and lower porosity can reduce the battery cost, enhance the specific energy, lower the battery mass but increase the performance instability. The reliability of the results in this study is proven by comparing estimated and actual commercial EV battery parameters. In addition to the positive electrode thickness and porosity, six other factors that affect the battery's cost and performance have been discussed. They include energy storage, negative electrode porosity, separator thickness and porosity, and negative and positive current collector thickness.

Keywords: Lithium-ion battery; Cost; Electrode thickness; Electrode porosity; Electric vehicle

1. INTRODUCTION

Lithium-ion batteries are the most advanced energy storage devices for electric vehicles (EVs), owing to their heigh energy and power densities. As the first generation of the EV battery, $LiMn_2O_4$ (LMO) and $LiFePO_4$ (LFP) do not have much of a presence in modern EVs due to their limited capacity. At present, the most impactful and fruitful positive electrode materials for EV applications are the $LiNiMnCoO_2$ (NMC) and $LiNiCoAlO_2$ (NCA).

One of the main drawbacks of EVs compared to internal combustion engine vehicles is the high price, mainly due to the expensive battery [1]. Cutting battery costs is therefore crucial to the promotion of EVs. The United States Advanced Battery Consortium (USABC) assessed that in order for EVs to be competitive in the marketplace, the selling price of EV batteries should be less than $100 per kWh in the long term [2]. However, the automakers said that Volkswagen's EV battery pack costs in 2017 and General Motors' in 2018 were $170-227 and $145 per kWh, respectively [3]. These prices are still well above USABC's target and must be reduced by a third or even doubled. Many works were published dealing with estimating battery costs [1,4–7]. One of the most comprehensive models on this topic is the open-access lithium-ion battery design and cost model (BatPaC) from the Argonne National Laboratory of the United States Department of Energy [6].

Based on battery cost estimation models, the researchers investigated the various factors that could reduce costs. Ciez et al. reported that the price of lithium plays a small role in the cost of the battery but producing the positive material in-house from precursors rather than purchasing it is an effective way of cutting costs [8]. The use of aqueous rather than organic solvents for electrode processing and reduction of the negative electrode electrolyte wetting and solid electrolyte interface (SEI) layer formation time were proved to be cost-saving [9]. Increasing production is another option to minimize costs. But after annual production exceeds 1 GWh, material costs will account for half of total overhead, and the impact of production on costs will be minimal [4].

The porosity and thickness of electrodes have significant impacts on a lithium-ion battery's performance [10]. Increasing electrode thickness has a positive effect on cost reduction has been proved by some studies [4,9,11]. However, the impact of electrode porosity and the cost of the latest NMC chemistry (NMC 811) have been much less discussed. In addition, the impact on performance while optimizing electrode porosity and thickness to reduce cost is also important but has rarely been studied.

This paper presents some potential solutions to lower the battery cost, increase specific energy, and reduce the mass by optimizing the material, electrode porosity, and thickness. The LMO, LFP, two of the most promising NMC materials (NMC 622 and NMC 811), NCA, and the blend system of NMC/LMO are selected for this study. The cost of battery packs with six positive electrode materials is estimated and compared. Moreover, we discuss the impact of electrode porosity and thickness on the cost of the NMC 811 battery. A set of real parameters of commercial EV batteries is used to validate the simulation results.

2. ELECTRIC VEHICLE (EV) BATTERIES USED IN THE STUDY

One of the oldest commercially used electrodes is spinel $LiMn_2O_4$ (LMO). It was first reported by Thackeray et al. in 1983 and commercialized by Moli Energy in 1996 [12]. The abundance and non-toxicity of manganese make LMO highly eco-friendly as well as low-cost (< 10 $/kg) [13]. The electrochemical and thermal stability resulting from the three-dimensional stable spinel structure gives LMO great safety [13]. The low capacity is considered to be the main disadvantage (100-150 Wh/kg). Besides, it suffers from Mn dissolution and relatively rapid capacity decay, leading to limited cycle life, typically in the range of 1000–1500 cycles [14,15]. To date, LMO batteries are primarily used in power tools and electric bicycles. LMO has been applied in EVs such as BMW i3, where they blend with other materials with high energy density but are more expensive and less safe. Table 1 provides a summary of main characteristics of commercially available Li-ion batteries.

TABLE 1: MAIN CHARACTERISTICS OF COMMERCIALLY AVAILABLE LI-ION BATTERIES [13–17]

	Specific energy (Wh/kg)	Safety	Durability	Material eco-friendly	Material cost
LMO	100-150	High	Low	High	Low
LFP	90-160	High	High	High	Low
NMC	140-200	Medium	Medium	Medium	Medium
NCA	200-250	Medium	Low	Medium	High

Olivine $LiFePO_4$ (LFP) was developed by Goodenough et al. in 1997 [18]. Since then, LFP is attracting much attention the past decade due to its high chemical stability, excellent thermal stability, and long cycle life (up to 2000 cycles) [14]. Furthermore, LFP relies on low-cost (~14 $/kg) and environmentally benign materials. However, $LiFePO_4$ has low conductivity and low diffusion coefficient of lithium-ion, which are the predominant factors restricting its high power applications [19]. Various approaches have been tried to improve the performance of this material, such as size and morphology control [20], conductive coating [21], and heterogeneous doping [22]. Despite these solutions, LFP for EV applications still limited by its low energy density (90 -160 Wh/kg) [13]. At present, the LFP battery in the field of EVs is not prominent, but in the field of electric bicycle and power supply system has a large potential market.

Layered $LiNiMnCoO_2$ (NMC) is one of the most successful positive electrodes with a relatively long cycle life (1000- 2000 cycles) and high energy density (140-200 Wh/kg) [23]. The material cost of NMC (~21 $/kg) is much higher than LMO and LFP [6]. The ratio between the Ni, Mn and Co will determine the performance of the positive electrode. Several successful combinations are NMC (3:3:3), NMC (5:3:2), NMC (6:2:2), and NMC (8:1:1). Researchers have proved that increasing the nickel content can increase the specific energy of NMC but at the cost of decreasing the stability [13,16]. NMC 333 and 532 are currently popular options in the NMC market. However, the market trend is towards higher Ni content electrodes (NMC 622, NMC 811) due to their higher specific energy and lower cost [23]. At present, the NMC 622 and NMC 811 battery have already been commercialized and supplied for EV application by LG Chem and Contemporary Amperex Technology Co. Limited, respectively.

Layered $LiNiCoAlO_2$ (NCA) is a relatively new positive electrode. NCA has outstanding specific energy, high specific power but limited cycle life (1000 - 1500 cycles) [14]. $LiNi_{0.8}Co_{0.15}Al_{0.05}$ is the most common form of NCA. The proportion of electrochemically active Al should not be too high. Otherwise, the reversible capacity of NCA will be significantly reduced and impurities will be formed [17]. Therefore, all combinations of NCA are considered as Ni-rich electrodes and suffer from relatively low stability. NCA is employed by Tesla in its EVs.

Several famous commercial EVs and their battery specifications are present in Table 2. The data are sourced from the official website of manufactures. NMC and NCA dominate the EV application owing to their high energy density. A few manufactures use the blend of LMO and NMC electrodes to take advantage of the best of both. LFP has been successful employed by Chinese EV maker BYD. EV manufacturers need to strike a balance between battery energy content and battery weight/volume. As shown in Table 2, the weight of batteries of relatively high capacity (60-100 kWh) for EVs is in the range of 430-700 kg.

TABLE 2: SEVERAL COMMERCIAL EVS AND BATTERY SPECIFICATIONS

Manufacturer	Name	Battery chemistry (cathode)	Energy storage (kWh)	Battery weight (kg)	Drive range (km)	Starting price (MSRP)
Tesla	Tesla Model 3 Long Range (2019)	NCA	75	480	523	$44,500
	Tesla Model S P100D (2019)	NCA	100	625	507	$133,000
General Motors	Chevrolet Bolt EV (2020)	NMC	66	430	414	$37,495
Volkswagen	VW e-Golf (2020)	NMC	35.8	318	190	$31,985
Nissan	Nissan Leaf (2018)	NMC	40	303	242	$30,875
Hyundai	Hyundai Ioniq Electric (2020)	NMC	38.3	341	272	$34,000
Ford	Ford Focus Electric (2018)	NMC	33.5	~300	180	$30,000
Fiat	Fiat 500e (2019)	NMC	24	ND[1]	134	$33,210
BMW	BMW i3 (2019)	NMC/LMO	42.2	278	245	$44,450
Daimler	Mercedes-Benz B-class (2017)	NCA	36	204	140	$39,900
Kia	Kia Soul (2020)	NMC	64	ND[1]	243	$18,485
BYD	BYD E6 (2020)	LFP	82	700	400	ND[1]

3. METHOD

3.1 Battery design

All the batteries in this study were fabricated using the Argonne National Laboratory model (BatPaC), which is one of the most comprehensive open-access li-ion battery design and cost models [4]. The model used in the experiment was an updated version from October 2020.

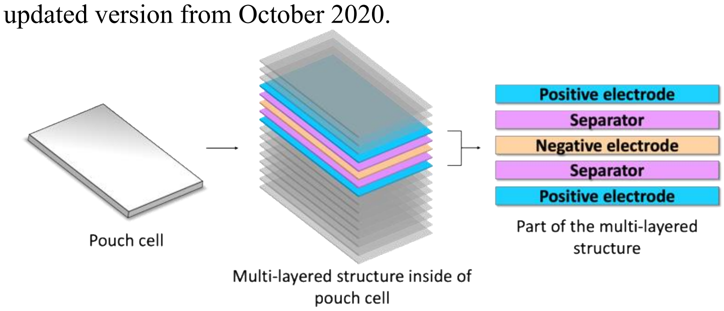

FIGURE 1: STRUCTURE OF POUCH CELL

The cell for the battery pack is designed as a prismatic cell in a stiff-pouch container (Figure 1). The pouch cell has been applied by several EVs, such as Nissan Leaf and Renault Zoe. Positive electrodes, separators, and negative electrodes form a multi-layered sandwich structure inside the pouch container. The electrodes consist of current collector coated with a composite including the active materials, carbon black, and polyvinylidene fluoride (PVDF) binder. The electrolyte is 1.2 M $LiPF_6$ in ethylene carbonate/ethyl methyl carbonate (EC/EMC). PP/PE/PP membrane is used as the separator. The positive and negative current collectors are aluminum and copper foil, respectively.

All batteries designed for this study have the same pack energy storage of 90 kWh, which is a high value that current electric vehicle batteries can achieve. Six types of positive electrode materials are selected: NMC 622, NMC 811, NCA, LFP, LMO and blend of NMC 532/LMO. The voltage (V) and

TABLE 3: BATTERY CHEMISTRY AND MAIN PARAMETERS FOR DESIGN

Battery	Cathode	Anode	Energy storage (kWh)	Positive electrode porosity (%)	Maximum positive electrode thickness (µm)
NMC 622	$Li(Ni_{0.6}Mn_{0.2}Co_{0.2})O_2$	Graphite	90	20, 30, 40, 50	50, 75, 100, 125,150
NMC 811	$Li(Ni_{0.8}Mn_{0.1}Co_{0.1})O_2$				
NCA	$Li(Ni_{0.8}Co_{0.15}Al_{0.05})_2$				
LFP	$LiFePO_4$				
LMO	$LiMn_2O_4$				
NMC 532/LMO	$Li(Ni_{0.5}Mn_{0.3}Co_{0.2})O_2$ (50%) + LiMn2O4 (50%)				

capacity (Ah) of the battery pack depend on different materials. Table 3 shows the chemistry and main parameters of six designed batteries. More detailed parameter settings for battery design are listed in Table A1.

3.2 Total cost calculation

Parameters generated by the battery design are used to calculate the cost of the battery pack. The material and purchased item requirements are determined by the pack design. The cost of these materials, the manufacturing cost of each processing step, and the battery pack's integration cost are added together to give the total cost of the battery pack (as shown in Table 4). The BatPaC manufacturing cost is calculated using the baseline plant's estimated manufacturing cost, with adjustments depending on the battery being designed. The baseline plant produces 100,000 packs per year of EV batteries with the following characteristics: cell chemistry $LiNi_{0.6}Mn_{0.2}Co_{0.2}$ - graphite (NMC622-G), 60-kWh pack energy, 220-kW power, 67-Ah capacity, and 240 cells per pack [6]. BatPaC assigns a characteristic processing rate to each step in the process (e.g., for materials preparation, weight prepared per year; for electrode coating, area coated per year). For each step, the manufacturing cost is calculated from the equation,

$$C = C_0\left(\frac{R}{R_0}\right)^p$$

Here, C and C_0 are the costs for the processing rate R and R_0, respectively, and p is the economy of scale power factor.

To facilitate the analysis of the results, the total battery cost is divided into four parts: (1) positive material cost, (2) other materials and purchased items cost, (3) manufacturing cost, and (4) pack integration cost. Each part of the cost item includes both direct and indirect costs. Given a large number of parameters in battery design and each manufacturer's different circumstances, we recommend that more attention be paid to the trends observed in the simulation results rather than the specific values simulated.

TABLE 4: BREAKDOWN OF COSTS [6]

Costs	Description	Method of Calculation
Positive material	Cost of positive active material.	Based on prices of materials, cost equations for purchased items and yields.
Other materials and purchased items	Cost of negative active material, carbon, binders, positive current collector, negative current collector, separators, electrolyte, cell hardware, module hardware, and battery jacket.	
Manufacturing	Cost of labor, capital equipment, building, land and utilities.	Cost estimation for each processing step at baseline rates adjusted for actual rates.
Pack integration	Cost of integrating battery pack into vehicle drivetrain, including battery management system, battery disconnects, and thermal management system.	Based on magnitude of battery current and the need to charge from the electrical grid.

4. RESULTS

4.1 Impact of positive electrode material on cost

The cost of a battery pack is calculated based on the design parameters in Table 3. The battery design determines the consumption of materials and purchased items. After that, the manufacturing cost and battery pack integration cost are added to the cost of these battery components to reach the total cost of a battery pack.

According to the results shown in Figure 2, the cheapest battery for a positive electrode thickness of 100 µm is the NMC 811. The NCA and NMC 622 batteries are slightly more expensive (+2.7% and +4.5%, respectively). The LFP battery is the most expensive one (+18.8%). The positive active material costs of LFP and LMO are lower than the NCA, NMC 622, NMC 811 and NMC 532/LMO, which is consistent with the information in Table 1. However, the entire cost for NMC and NCA batteries is lower since other materials and purchased items portions as well as the manufacturing fee are cheaper.

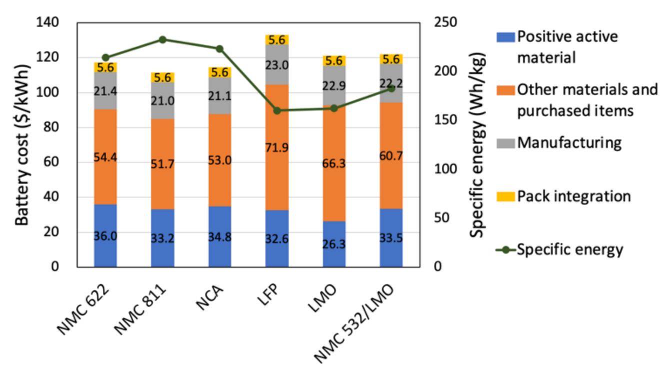

FIGURE 2: BATTERY COST BREAKDOWN FOR EACH MATERIAL (POSITIVE ELECTRODE THICKNESS LIMITATION = 100 mm, POSITIVE ELECTRODE POROSITY = 30%)

Although NMC 811 is 60% more expensive than LFP ($22/kg versus $14/kg, respectively), the total cost of the positive active material increases by only 2%. Since NMC 811 material has a 1.5 times higher capacity than LFP (212 mAh/g versus 150 mAh/g, respectively), the less positive active material is needed to achieve the battery's target energy.

The more energetic the material, the less mass is required to produce the same amount of energy. Therefore, the LFP and LMO battery packs' volume and weight can be much higher than others. This can be proved by the battery pack's specific energy in Figure 2 (green line). Higher specific energy represents less weight of the battery pack since all the batteries have the same energy content. The LFP and LMO positive active materials require a larger amount and area than other high energy density materials, resulting in the additional cost increase for inactive components and manufacturing process, such as the carbon additive and electrode coating cost.

4.2 Impact of positive electrode porosities and thicknesses on cost

Now, let's focus on one of those materials and the impact of electrode porosity and thickness on the cost. We changed the porosity of the NMC 811 positive electrode while keeping the negative electrode's porosity at 25% as well as the negative-to-positive electrodes capacity ratio (N/P capacity ratio) constant. According to Figure 3, the cost increase between the ranges of 20% and 50% is 10.3%. Low porosity represents the high electrode density (quantity of active materials/unit volume). The electrode area increases with the porosity due to the constant thickness and cell energy content. Correspondingly, the costs that increase with porosity are inactive components (current collectors, carbon additive, electrolytes, separators) and electrode processing. With a fixed negative electrode porosity, higher positive electrode porosity can cause the decrease of specific energy.

The cost per kilowatt-hour of six battery packs according to the positive electrode porosity is shown in Figure 4. The cost reduction between the ranges of 20% and 50% is: 10% for NMC 811, 12% for NMC 622, 11% for NCA, 18% for LFP, 20% for LMO, and 15% for NMC 532/LMO. It can be found that the variation of the positive porosity has a stronger effect on the low specific energy batteries, such as LFP and LMO. Figure 4 suggests that the positive electrode porosity affects the comparison of different battery costs. For example, the LMO battery is cheaper than the NMC 532/LMO with a positive electrode porosity of 20%. However, it is more expansive than NMC 532/LMO when the positive electrode porosity change to 50%.

Figure 5 shows the cost breakdown for the same cell (NMC 811), with five different electrode coating thicknesses. The actual electrode thicknesses are summarized in Table 5. The thickness limit of the positive electrode of NMC 811 is changed with the same thickness ratio of the positive and negative electrodes (N/P thickness ratio). The N/P thickness ratio was set as 1.18. The maximum thickness of the positive electrode of our designed 90kWh NMC 811 battery is 144 μm (Table 5). Therefore, the actual electrode thickness did not change after the limitation reaches 150 μm.

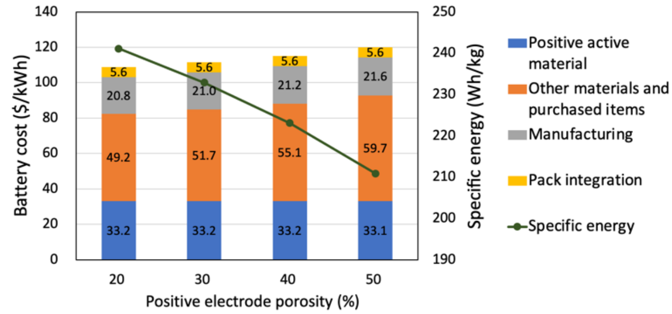

FIGURE 3: BATTERY COST BREAKDOWN AND SPECIFIC ENERGY FOR NMC 811 IN DIFFERENT POSITIVE ELECTRODE POROSITY (POSITIVE ELECTRODE THICKNESS LIMITATION = 100 mm)

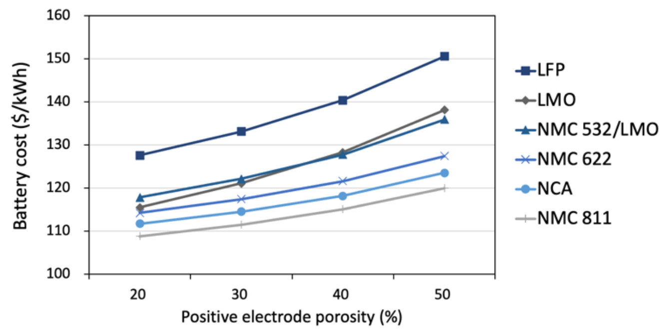

FIGURE 4: BATTERY COST COMPARISON FOR SIX POSITIVE ELECTRODE MATERIALS AND A VARIABLE POSITIVE ELECTRODE POROSITY

According to Figure 5, the cost reduction between the ranges of 50 and 150 μm is 15.2%. As the thickness of the electrode increases, the consumption of inactive parts decreases, and the cost of other material and purchased items was obviously affected. The cost of electrode processing is also decreased by reducing the electrode surface area and the processing time for stacking the electrodes and separator sheets [11]. In addition, the specific energy of the NMC 811 battery pack is significantly improved by achieving a thicker positive electrode due to the reduction of inactive components ratio.

Figure 6 presents the battery cost comparison for six positive electrode materials. The reduction between the ranges of 50 μm and 150 μm is 15% for NMC 811, 17% for NMC 622, 16% for NCA, 27% for LFP, 30% for LMO, and 23% for NMC 532/LMO. Similar to porosity, fluctuation in positive electrode thickness has a greater impact on low specific energy materials. Figure 5 also indicates that the positive electrode thickness setting affects the cost comparison of different electrode materials.

Our results suggest that the use of larger electrode thicknesses leads to increases in energy density and decreases in cost. However, some challenges hinder the application of thick electrodes. There are challenges for the fabrication of robust thick electrode, such as wetting the electrode's full porosity, achieving a defect-free coating, and avoiding breakage and delamination of the electrode during drying [24].

TABLE 5: THICKNESS OF THE POSITIVE AND NEGATIVE ELECTRODES FOR NMC 811 AT DIFFERENT POSITIVE ELECTRODE THICKNESS LIMITATION

Limit of positive electrode thickness (μm)	Actual positive electrode thickness (μm)	Actual negative electrode thickness (μm)
50	50	59
75	75	89
100	100	118
125	125	148
150	144	170
200	144	170
300	144	170

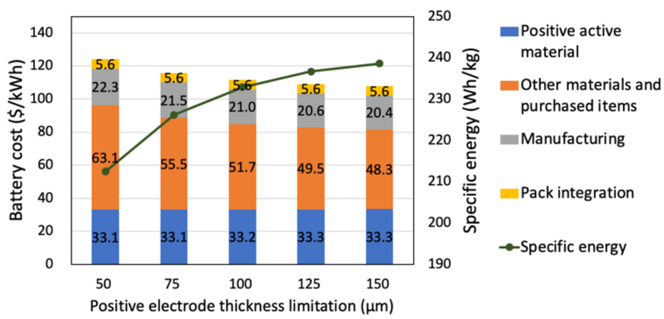

FIGURE 5: BATTERY COST BREAKDOWN AND SPECIFIC ENERGY FOR NMC 811 IN DIFFERENT POSITIVE ELECTRODE THICKNESS LIMITATION (POSITIVE ELECTRODE POROSITY = 30 %)

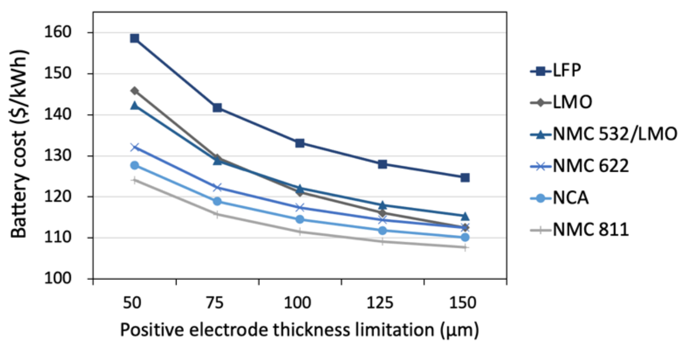

FIGURE 6: BATTERY COST COMPARISON FOR SIX POSITIVE ELECTRODE MATERIALS AND A VARIABLE POSITIVE ELECTRODE THICKNESS LIMITATION

4.3 Effect of electrode porosities and thicknesses on battery properties

The higher thickness and lower porosity can increase the amount of active materials in the electrode in a fixed volume, thereby enhancing the specific energy and reducing the battery mass. The specific energy and mass changes of six batteries are presented in Figure 7. According to the figure, Ni-rich positive materials (NMC 811, NMC 622 and NCA) allow the battery packs lighter. However, due to the limited utilization of active materials, active material loading increases in severe capacity loss at high current rates.

In low porosity electrodes, because of the small space between neighboring particles, the transport of lithium-ion has been limited. Kitada et al. reported that the electrode with lower porosity presented a worse discharge capacity at a high current rate, despite the larger theoretical capacity [25]. The poor capacity retention of low porosity electrodes results in unstable battery performance.

With the increase of electrode thickness, the lithium ion transport distance and resistance increase proportionally. The longer diffusion distance can make electrochemical reaction unevenly taken place and increased thermal instability, resulting in lower power output and earlier discharge stop, especially at high current rates [26].

Previous results of this study indicate that high specific energy, low cost and low battery mass are positively correlated. Therefore, future optimization of battery design in terms of electrode thickness and porosity should carefully consider the trade-off between the specific energy and performance instability.

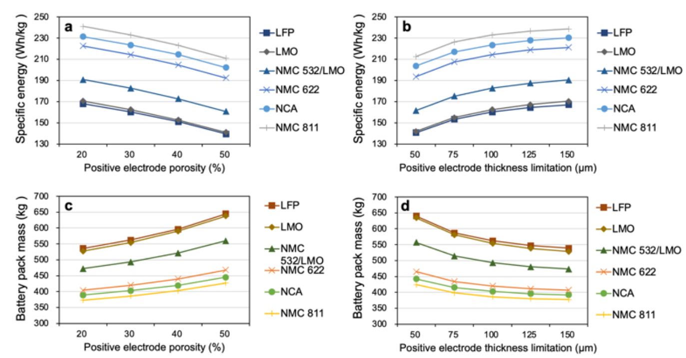

FIGURE 7: SPECIFIC ENERGY AND MASS COMPARISON FOR SIX POSITIVE ELECTRODE MATERIALS

4.4 The impact of other parameters and sensitivity analysis

In this study, only the positive electrode thickness and porosity are discussed in detail since they have a considerable effect on both cost and performance. In addition to these two parameters, six other factors affect the battery's cost and performance, including energy storage, negative electrode porosity, separator thickness and porosity, and negative and positive current collector thickness. Figure 8 is used to depict the sensitivity of the cost per kWh and the specific energy to changes in selected variables. Each bar indicates the range of cost or specific energy produced when each design variable is set to the base value, the low-end (-50%), and the high-end (+50%), with all other variables held constant. The blue bar indicates that the value is produced from the low-end and the orange bar indicates that the value is produced from the high-end. The related data are listed in Table A2. It is evident that battery energy storage plays a considerable role in costs. As a pre-set parameter, we left it out of the discussion.

The effect of negative electrode porosity change is also an interesting way to improve battery design. Higher negative electrode porosity can lead to higher cost and lower specific energy. The separator thickness and porosity, negative/positive current collector thickness have low effects on cost but not negligible impacts on performance. These parameters offer opportunities to improve the battery, with different cell behavior impacts than positive electrode thickness and porosity. Figure 8b shows that the battery with a thicker negative/positive current collector, thicker separator and higher separator porosity suffer from lower specific energy.

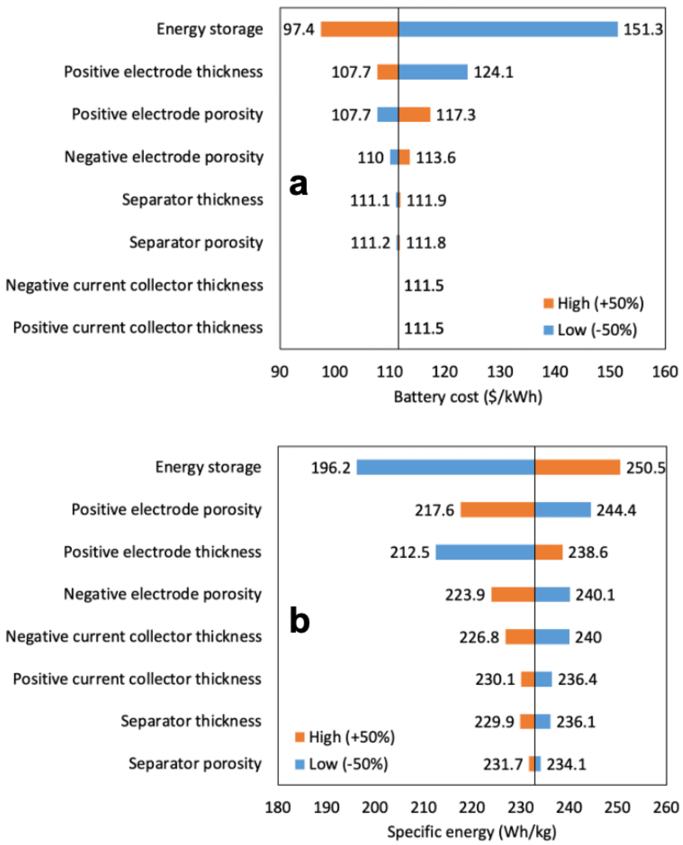

FIGURE 8: SENSITIVITY ANALYSIS OF THE (A) COST AND (B) SPECIFIC ENERGY FOR THE NMC 811 BATTERY PACK

4.5 The cost and weight estimation of commercial EV batteries

To better understand the performance of BatPaC model, we estimated the cost and weight of several commercial EV batteries based on their chemistry and energy content in Table 2. Since manufacturers do not share their battery designs and formulations, the NMC, NCA and NMC/LMO materials are assumed as the NMC 622, NCA and NMC 532/LMO in Table 3. Other parameters are taken from Table A1.

The results are summarized in Figure 9. The actual vehicle price, manufacturer's suggested retail price, is selected to compare with estimated battery cost due to the insufficient data of actual battery price. According to Figure 9a, the fluctuation of actual vehicle price is basically the same as that of battery pack price estimated in this study, which suggests that battery cost is one of the key factors affecting the price of EVs. The actual weight of most EV batteries is significantly higher than the estimated value (+34% on average), but the trend is consistent (as shown in Figure 9b), which proves the reliability of the simulation results. In addition to the differences caused by unknown battery design parameters, other reasons are worth investigating.

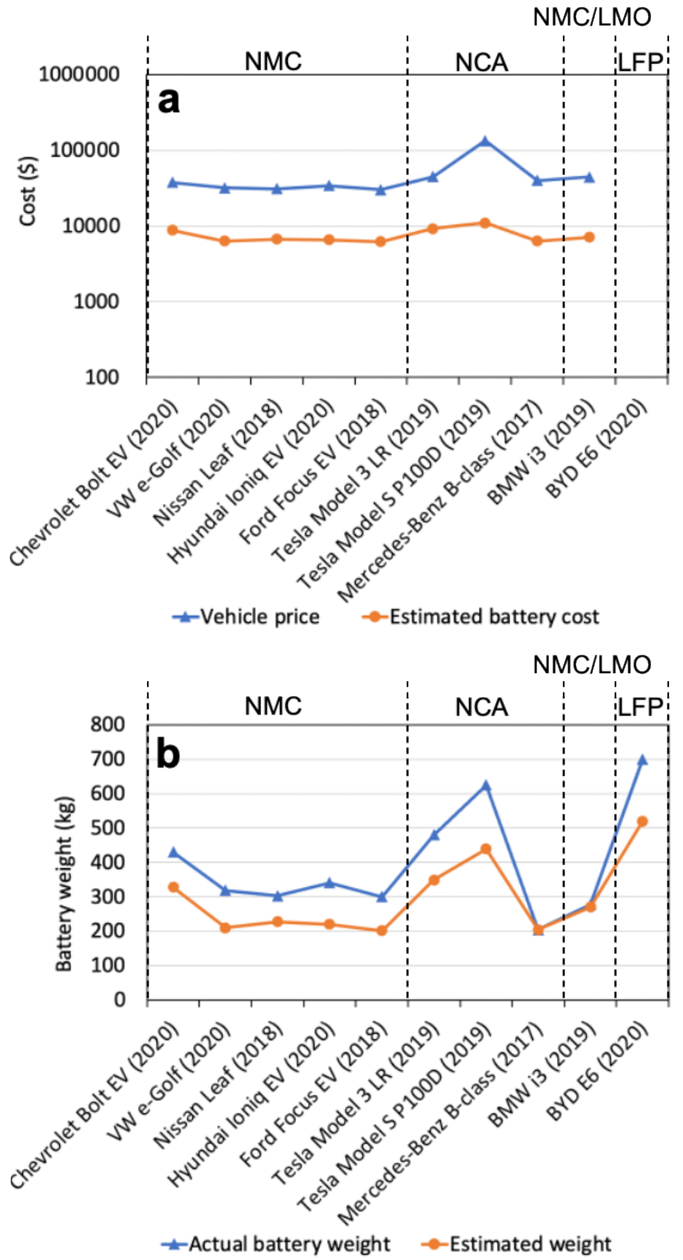

FIGURE 9: ESTIMATION OF THE (A) COST AND (B)WEIGHT FOR THE COMMERCIAL EV BATTERIES

5. CONCLUSION

The objective of this study is to investigate the key parameters of battery cost and performance and to highlight the design trade-off. A detailed cost breakdown was given for the lithium-ion battery pack, which focuses on comparing positive electrode materials, increasing the thickness of the electrode, and reducing positive electrode porosity.

The order battery pack cost for the positive active materials is NMC 811 < NCA < NMC 622 < LMO < NMC 532/LMO < LFP. Nickel-rich batteries allow the battery pack cheaper. The LFP battery costs 18.8% more than NMC 811 battery, even though its positive active material cost is cheaper. The high energy density of nickel-rich electrodes offers the potential for higher battery cost reductions. However, their safety issues due to reactivity and thermal instability still need to be addressed. High electrode thickness and low porosity are attractive for reducing battery cost, and weight but are detrimental to performance stability and are limited by current fabrication technology.

The trade-off between cost/energy ratio and instability needs to be considered when optimizing positive electrode thickness and porosity in the future. In addition, improving the manufacturing process and upgrading the design of the electrodes to make thick and dense electrodes commerciale are also vital to the problem. Other cost and performance drivers, such as negative electrode porosity, separator thickness and porosity, and negative and positive current collector thickness, have relatively weak effects on cost and performance but offer additional ideas and potential for optimal battery design that are worth exploring in depth.

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APPENDIX

TABLE A1: ALL THE PARAMETERS FOR BATTERY DESIGN*

Parameter	Value
Energy storage (kWh)	90
Positive electrode porosity (%)	30 (baseline)
Positive electrode thickness limitation (μm)	100 (baseline)
Negative-to-positive electrode capacity ratio	1.1
Negative electrode porosity (%)	25
Positive current collector thickness (μm)	15
Negative current collector thickness (μm)	10
Separator thickness (μm)	15
Separator porosity (%)	50
Target battery pack power at 20% SOC, kW	200
Number of cells per pack	400
Number of modules per pack	20
Number of cells per module (total)	20
Number of cells in parallel group in module	4
Number of modules in row	5
Number of rows of modules per pack	4
Number of modules in parallel	1
Number of packs manufactured per year	100000
Energy requirement for a UDDS cycle, Wh/mile	250

* Other parameters are default value in model

TABLE A2: SENSITIVITY ANALYSIS OF THE COST AND SPECIFIC ENERGY FOR THE NMC811 BATTERY PACK

Factor	Low-end			Baseline			High-end		
	Value	Cost ($)	Specific energy (Wh/kg)	Value	Cost ($)	Specific energy (Wh/kg)	Value	Cost ($)	Specific energy (Wh/kg)
Energy storage (kWh)	45	151.3	196.2	90	111.5	232.9	135	97.4	250.5
Positive electrode porosity (%)	15	107.7	244.4	30	111.5	232.9	45	117.3	217.6
Positive electrode thickness limitation (μm)	50	124.1	212.5	100	111.5	232.9	150	107.7	238.6
Negative electrode porosity	12.5	110	240.1	25	111.5	232.9	37.5	113.6	223.9
Positive current collector thickness (μm)	7.5	111.5	236.4	15	111.5	232.9	22.5	111.5	230.1
Negative current collector thickness (μm)	5	111.5	240	10	111.5	232.9	15	111.5	226.8
Separator thickness (μm)	7.5	111.1	236.1	15	111.5	232.9	22.5	111.9	229.9
Separator porosity (%)	25	111.2	234.1	50	111.5	232.9	75	111.8	231.7