Old Dominion University

Engineering Management and Systems Engineering Department

4680 Battery Cell Market Analysis and Supply Chain Proposal

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Introduction

In part because of the rise of Tesla within the last two decades, the development and demand for battery cells for use in electric vehicles (EVs) have increased tremendously. As a result of Tesla's and Panasonic's industry-leading designs and technologies in the fields of EVs and batteries, other major car companies have decided to conform to the standard that Tesla has set by incorporating similarly modeled battery cells into their own EVs. For some EV manufacturers, this is the most reasonable supply chain decision.

As a result, the market for the most efficient battery model will have no shortage of demand in the near future. Thus, the purpose of this report is to provide 1) an analysis of the battery industry, 2) a product breakdown of the latest 4680 cell model, and 3) a proposal for a supply chain to determine whether or not to enter the US EV battery market.

Industry Analysis

Market Information

In 2021, the global EV battery market was valued at 27.30 billion USD (4), with the vast majority of cell production taking place in China. Geographically, the production of cells is distributed as follows:

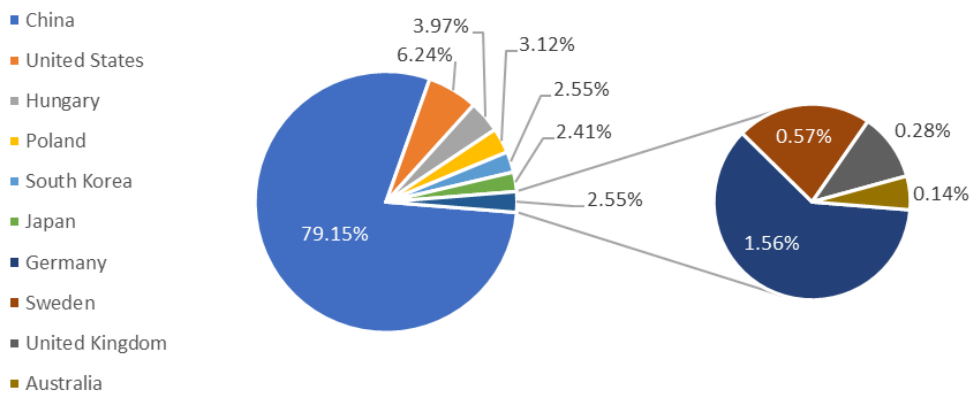

Figure 1. 2021 geographic market distribution by manufacturing capacity (% of GWh) (1).

Of the 27.30 billion USD, the North American (NA) EV battery market contributed 1.82 billion USD that total (10). Given that Tesla-Panasonic produced about 84% of the total GWh in NA and Canada and Mexico produce less than 1 GWh each in 2021 (1), the US and NA valuations approximate each other. The majority of this valuation can be assumed to be from the production of 1865, 2170, and 4680 cell models.

As of yet, the 4680 battery cell is still in development by Tesla, though early versions have made it into some of Tesla's most recent EV models. As a result, its main developmental competitors are other next-generation batteries, such as GM's Ultium (7) and CATL's Kirin (12). Within the manufacturing sector, competition occurs between developers of similar battery models. The battery market consists mainly of substitute products like the 1865 and 2170 cell models, the models that preceded the 4680 in use in EVs and are still the most common types available.

Industry Forecast

Based on sales over the last ten years, the battery electric vehicle (BEV) market in the US might seem to be growing exponentially. However, a ten-year forecast using an exponential model would suggest BEV sales numbers that would far exceed the average annual sales of all motor vehicles in the US over the last century, and recent motor vehicle sales data shows that the market is trending downwards. Thus, it would be more conservative and likely more accurate to model the sales data using Holt's Model, as follows:

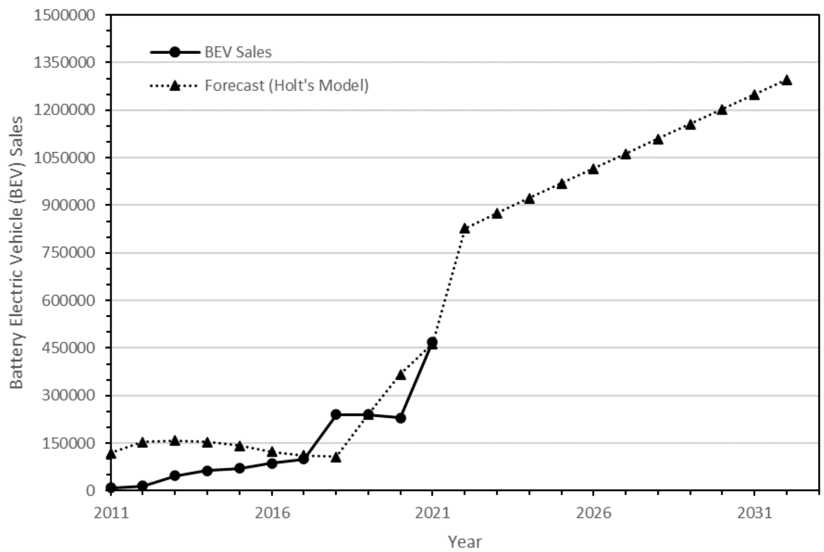

Figure 2. US Battery electric vehicle (BEV) annual sales forecasts using Holt's Model (6).

Based on the results of this ten-year forecast, BEV sales will reach nearly 1.3 million units in annual sales. Assuming a conservative estimate of 5000 cells per unit, this suggests an annual cell demand of about 6.5 billion cells in 2032. With this amount of demand, battery materials would likewise be in high demand, and plenty of competitors may look to enter the market.

Porter's Five Competitive Forces

Threat of New Entrants

While the global market for EV cells is dominated by companies headquartered in Asia, the US market has only a handful of competitors that are dedicated to the production of EV cells. However, several generic battery companies in the US have the technology and manufacturing infrastructure to potentially transition into EV cells if the market becomes more attractive. Since the general construction of EV cells is common knowledge within the industry, the threat of new entrants into the market is potentially high.

Threat of Substitutes

The threat of substitutes largely depends on the goals of the EV manufacturers. Currently, the trend for EV cell implementation is to either create proprietary cell technology or source cells from the industry leaders. As such, the threat of substitute products is very low, as most viable substitutes come from previous generations of cell construction, which is typically unattractive to the end customer.

Bargaining Power of Customer

The bargaining power of the customer is very high in the EV battery industry. Committing to the production of a specific cell model immediately limits the number of customers that are able to buy that cell. In this case, the primary customers of the 4680 cell are Tesla and other EV manufacturers that plan to conform to Tesla's battery technology. That being said, battery demand is high in service of Tesla alone, so the scarcity of the product may allow the manufacturer some leverage in bargaining.

Bargaining Power of Suppliers

The bargaining power of suppliers is also high. Due to the exploding demand for lithium-ion batteries in recent years, the production of metals like lithium and cobalt has yet to catch up to the needs of the battery industry. Thus, many other cell manufacturers may offer increasingly competitive prices, leaving the suppliers with a variety of options.

Competitive Rivalry

Even given the large capacities of Chinese and Japanese cell manufacturers, competitive rivalry is moderately low. Competition is generally only present if manufacturers are producing the same model of cell, as the applications of each model vary greatly. For the 4680 model, supply capacity is far lower than demand and is not anticipated to catch up in the near future. Thus, even with the number of manufacturers already in the industry, the effects of competition should not be as pronounced.

Strategy

For a cell manufacturer newly entering the US market, it is reasonable to capture between 0.5% to 0.6% of the global market or about 1% of the US market. Lithium-ion cell manufacturers like Romeo Power which have been around for less than a decade sit at about 0.5% to 1.5% of the general US battery industry market cap. To accomplish similar results, the starting capital for this project is estimated to be around 2 to 3 million USD.

By producing a specific type of cell model, the strategic position of this venture targets a specific client base in an emerging market, differentiating itself from historic battery manufacturers in the US. As a company established in the US market, the objective is to optimize customer value by manufacturing and shipping within the region, thus avoiding or reducing costs normally incurred by international shipping. Due to the geographical location of the market in the US, it is anticipated that the capacity of the supply chain will naturally be lower than a similarly constructed network in Asia. However, since the primary customer base is also in the US, the supply chain has the potential to be more responsive, which may prove to be an advantage in an uncertain, emerging market.

Product Description

The 4680 battery is a cylindrical lithium-ion cell used mainly in the construction of Tesla EV battery arrays. The reversible nature of the reduction of lithium ions makes it a rechargeable cell, which is critical for applications where the replacement of the battery array is difficult or impossible. EV designs integrate thousands of cells, so it is important for the batteries to have a high energy density and low form factor. Thus, the 4680 model is a step forward in both of these aspects when compared to the previous 1865 and 2170 models.

Multilevel Bill of Materials (BOM)

The parts required to construct a 4680 battery cell are decomposed in Figure 3. Since the cell design is still in development, some miscellaneous components that are difficult to verify have been omitted and are considered negligible in terms of cost. A more detailed breakdown of materials and cost can be seen in Appendices A and B.

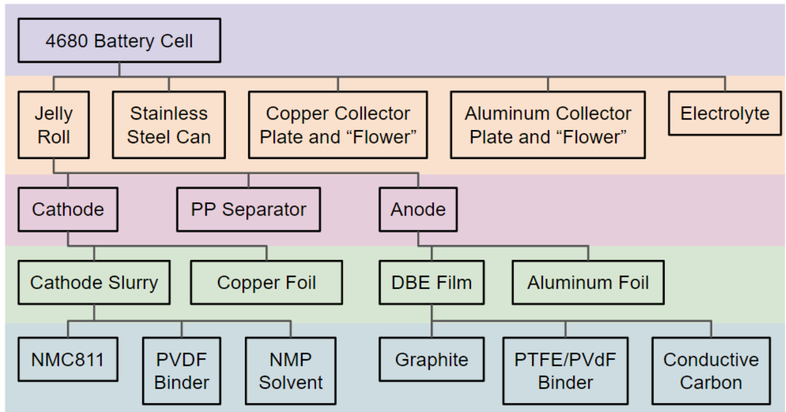

Figure 3. Multilevel bill of materials (BOM) for a 4680 cell (5).

All of the materials in the BOM are sourced from individual manufacturers; in other words, the scope of this system is the production of the jelly roll and the assembly of the final battery. For each material in the second and third levels of decomposition, suppliers can be found in the supplier index in Appendix D. This supplier index is compiled under a few assumptions, as follows:

- The cathode and anode chemical suppliers can supply all components of each electrode, either individually or premixed.
- The aluminum and copper foil suppliers can supply a variety of foil thicknesses and can produce foil parts as well as foil rolls.
- Suppliers within a particular material category can supply any specialized materials that the original Tesla-Panasonic design may be using.

Referencing the supplier index in Appendix D, all of the listed manufacturers or distributors are located in the continental United States, meaning that all supplies can be transported via road freight, the most generally cost-effective mode of transportation. A full truckload shipping across the midwest is about 1200 USD (11).

Likewise, the distribution mode for all materials listed is by direct channel. To further reduce cost, a third-party logistics (3PL) agency such as C.H. Robinson, Expeditors, or UPS Supply Chain Solutions can be used to handle transportation and intermediary storage.

As an estimate for facilities and machinery cost, a similar project for Tesla was estimated to cost at least 1.5 million USD (9). Sample production line machinery may include mixers, furnaces, coaters, heaters, rolling presses, slitting machines, ultrasonic or laser welders, winding machines, grooving machines, electrolyte fillers, and sealers (2). Additionally, assembly line staples like conveyors and robotic arms are a given, and battery testing equipment would be needed for quality assurance.

Supply Chain Proposal

Taking into account the BOM and corresponding analysis, the proposed supply chain model can be seen in Appendix C. In short, the 4680 battery materials are sourced through manufacturers that convert raw materials into bulk processed components. These are stored and transported through a 3PL partner, who then delivers them to our warehouse and production facility for assembly. As shown by the locations of the suppliers in Appendix D, our facility will likely be located in the midwestern United States, particularly in states like Indiana, Ohio, or Kentucky. Since there are many more supplier locations than customer locations, minimizing supplier distance should minimize transportation costs and increase responsiveness in receiving inventory, which is critical to the operation, as shown in the performance metrics.

Performance Metrics

As shown in Appendix E, the majority of supply chain metrics are focused on inventory. After a battery is assembled, its ability to hold charge gradually decreases over time regardless of use; this is known as the cell's state-of-health (SOH) (3). Though this degradation is not fast by any means, this property makes inventory management critical. Keeping completed cells in inventory for months or years may degrade them to the point that they are no longer acceptable to customers, resulting in inventory shrinkage and dead stock. Cell materials prior to assembly are more resistant to prolonged storage, thus the rate at which incoming inventory is converted into finished products should be closely monitored. Other than inventory, transportation is also a key metric due to this supply chain's high dependence on road freight.

Early on in the development of this supply chain, it is expected that the business will perform on the less optimal end of the industry estimates due to learning and human error. As more systems are refined and standardized, the supply chain can reasonably perform at the higher end of the industry. Of the industry metrics, the strategic position of this supply chain can exceed throughput metrics like sell-through rate, cash conversion cycle, order fill rate, and dead stock by maintaining smaller inventory volumes; this results in a trade-off in efficiency, as incoming inventory would be ordered in smaller amounts.

While the demand for 4680 battery cells looks positive, the supply chain is not without its risks. The design of the supply chain relies largely on raw materials that are in scarce supply, like lithium and cobalt; these materials are sensitive to disruptions in the global market. Though this is unavoidable, the supply chain design can mitigate this effect by diversifying the number of manufacturers; this may result in an increase in cost due to smaller order amounts, but minimizes the extreme cases where manufacturers cannot fulfill an order.

Conclusion

Overall, the battery industry over the next decade seems to be growing at a rapid pace, and EVs are becoming increasingly available to the end consumer. Many nations are moving to impose clean energy and green initiatives that will necessitate the advancement of EV and battery-charging infrastructure. The global production capacity of cells, particularly next-generation cells like the 4680 model, will need to expand in accordance. Thus, investing in the facilities and equipment needed to produce battery cells will yield returns for years to come.

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<u>**Appendices**</u>

Appendix A: Tesla 4680 cell material breakdown

4680 Total Battery Mass (g)	355
304 Stainless Steel Can:	
Diameter (Outer, mm)	46
Height (Outer, mm)	80
Thickness (um)	600
Diameter (Inner, mm)	44.8
Height (Inner, mm)	78.8
Volume (mm^3)	8737.7
Density of 304SS (kg/m^3)	8000
Can Mass (g)	69.9

Notes and Assumptions:
The can is approximated as a uniform, hollow cylinder.
Jelly roll dimensions are based on rough measurements.
Unknown materials are assumed within reason.
Mixed or hybrid materials are approximated as the material of greatest content percentage if over 90%.
Collector plate diameters are assumed to be equal to the interior of the can.

Jelly Roll Length (m)	3.35
Jelly Roll Width (mm)	65

Jelly Roll Materials:	**Copper Foil**	**Aluminum Foil**	**PP Separator**	**Cathode (NMC811)**	**Anode (Graphite)**
Thickness (um)	8	15	16	85	85
Porosity (%)	--	--	50	--	--
Volume (mm^3)	1742	3266.25	1742	18508.75	18508.75
Density (g/cm^3)	8.96	2.7	0.91	2.2	2.26
Mass (g)	15.6	8.82	1.59	40.7	41.8

Collector Plates and "Flowers":	**Copper**	**Aluminum**
Diameter (mm)	44.8	44.8
Thickness (um)	260	400
Volume (mm^3)	409.8	630.5
Plate Mass (g)	3.67	1.70

Electrolyte:	
Internal Volume (mm^3)	124214.5
Electrolyte Volume (mm^3)	79406.3
LiPF6 Electrolyte Density (g/cm^3)	1.5
Electrolyte Mass (g)	119.1

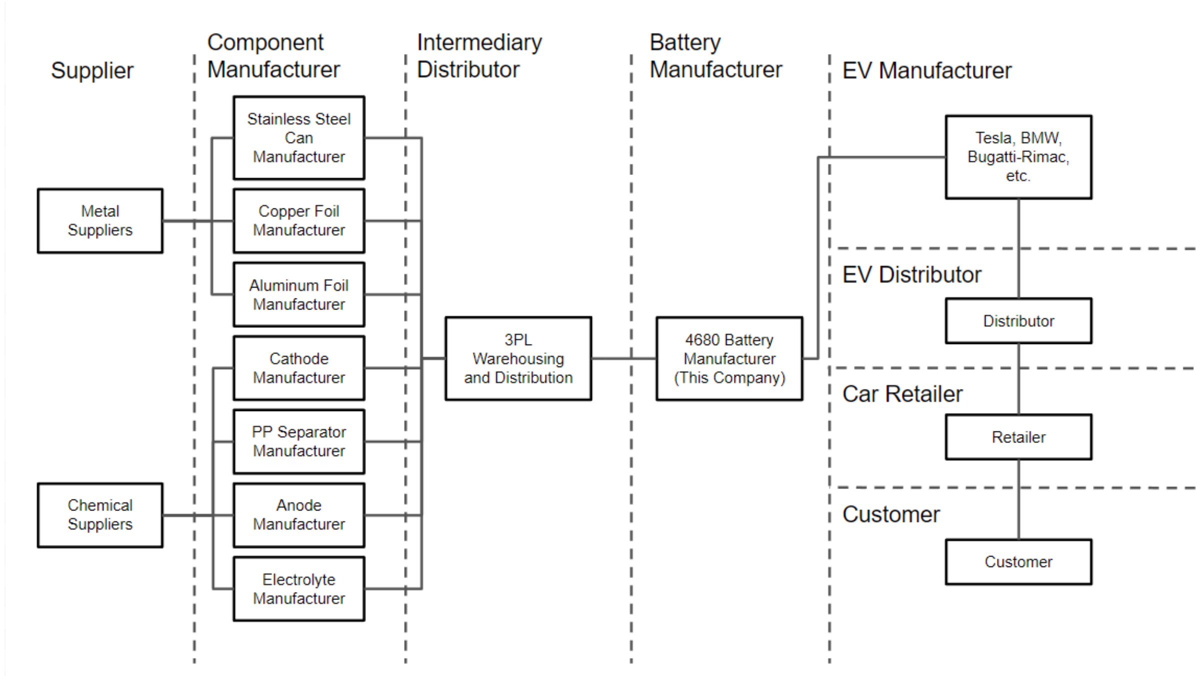
Unaccounted Mass (g)	52.1
% Unaccounted Mass	14.7

Unaccounted mass can be contributed to errors in simplification and estimation.

Appendix B: Tesla 4680 cell material cost breakdown

4680 Battery Cell Bill of Materials	Price Estimate	$/kg	g/battery	$/battery
304 Stainless Steel Can	$2/kg	2	69.9	$0.14
Copper Collector Plate and "Flower"	~$9/kg	9	3.67	$0.03
Aluminum Collector Plate and "Flower"	~$2.2/kg	2.2	1.70	$0.00
Electrolyte	$100/kg	100	119.1	$11.91
Jelly Roll				
PP Separator	$1.30/kg	1.3	1.59	$0.00
Cathode				
Copper Foil	$16.85/kg	16.85	15.6	$0.26
Cathode Slurry				
NMC811	$35/kg	35	36.6	$1.28
PVDF Binder	$45/kg	45	2.04	$0.09
NMP Solvent	$1/kg	1	2.04	$0.002
Anode				
Aluminum Foil	$2.2/kg	2.2	8.82	$0.02
DBE Film				
Graphite	$8/kg	8	37.6	$0.30
PTFE/PVdF Binder	~$45/kg	45	2.09	$0.09
Conductive Carbon	$5/kg	5	2.09	$0.01
Material prices estimated using Alibaba.com	Material Cost/Battery based on BOM:			$14.15
	Tesla Estimated Cost per kWh			$132
	Average Wh per Battery			98
	Tesla Estimated Cost/Battery			$12.94

Appendix C: Proposed supply chain model



Appendix D: Supplier index

Copper Foil Suppliers	Locations
Goodfellow Corp.	Coraopolis, PA
Continental Steel & Tube Co.	Fort Lauderdale, FL
All Metal Sales, Inc.	Cleveland, OH
California Metal & Supply, Inc.	Santa Fe Springs, CA
Admat, Inc.	Norristown, PA
Saunders, Inc.	Irwindale, CA/Lombard, IL

Aluminum Foil Suppliers	Locations
Thin Metal Sales, Inc.	Chino, CA
Lawrence & Frederick, Inc.	Streamwood, IL
All Metal Sales, Inc.	Cleveland, OH
California Metal & Supply, Inc.	Santa Fe Springs, CA
Saunders, Inc.	Irwindale, CA/Lombard, IL

Electrolyte Suppliers	Locations
Static Power, Inc.	Phillipsburg, NJ
Colonial Chemical Corp.	Tabernacle, NJ
Haviland Enterprises, Inc.	Grand Rapids, MI
Octagon Process, Inc.	Edison, NJ
Wego Chemical Group Inc	Great Neck, NY

PP Separator Suppliers	Locations
Asahi Kasei America, Inc.	Novi, MI
Celgard, LLC	Charlotte, NC/Concord, NC

Can Suppliers	Locations
Hudson Technologies	Ormond Beach, FL
Gem Manufacturing Co., Inc.	Waterbury, CT
Trans-Matic	Holland, MI
The National Die Co.	Wolcott, CT
American Epoxy & Metal, Inc.	Yonkers, NY
Peterson Manufacturing, LLC	Sarasota, FL
National Mfg. Co., Inc.	Chatham, NJ
Cly-Del Manufacturing Co.	Waterbury, CT
Hylie Products, Inc.	Watertown, CT
Accurate Forming, Inc.	Hamburg, NJ

Anode Suppliers	Locations
MSE Supplies LLC	Tucson, AZ
SurgePower Materials Inc.	San Marcos, TX
Haviland Enterprises, Inc.	Grand Rapids, MI

Cathode Suppliers	Locations
MSE Supplies LLC	Tucson, AZ
AVP Engineered Coatings	Akron, OH
Haviland Enterprises, Inc.	Grand Rapids, MI

Companies sourced from listings on Thomas https://www.thomasnet.com/

Appendix E: Supply chain performance metrics and industry comparison

Performance Metric	Formula	Industry Benchmark	Estimate
Incoming Inventory Metrics			
Sell-through Rate	Number of Units Sold / Effective Number of Units Received x 100%	40% to 80%	40%
Cash Conversion Cycle	Days Inventory Outstanding + Days Sales Outstanding - Days Payable Outstanding	30 to 45 days	45 days
Inventory Turnover	Cost of Goods Sold / Average Inventory	5 to 10	5
Outgoing Inventory Metrics			
Order Fill Rate	Total Number of Customer Orders Shipped / Number of Customer Orders Placed x 100%	95% to 98%	98%
Inventory Shrinkage	(Ending Inventory in Period - Actual Inventory in Period) / Ending Inventory in Period x 100%	1% to 2%	1%
Dead Stock	(Amount of Unsellable Stock in Period / Amount of Available Stock in Period) x 100%	20% to 30%	30%
Overall Inventory Metrics			
Inventory to Total Assets	Value of Inventory / Value of Total Assets x 100%	1%	5%
Accuracy of Forecasted Demand	(Actual Demand - Forecasted Demand) / Actual Demand x 100%	10%	10%
Transportation Metrics			
Freight Bill Accuracy	Error-Free Bills / Total Bills x 100%	98%	98%
Shipping Time	Time Order Received - Time Order Shipped	5 to 7 days	5 to 7 days