The Lithium Ion Battery and the EV Market:

The Science Behind What You Can't See

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Kimberly Berman
Special Projects Analyst
BMO Nesbitt Burns Inc.
kimberly.berman@bmo.com
(416) 359-5611

Jared Dziuba, CFA
Oil & Gas Analyst
BMO Nesbitt Burns Inc.
jared.dziuba@bmo.com
(403) 515-3672

Colin Hamilton
Global Commodities Analyst
BMO Capital Markets Limited
colin.hamilton@bmo.com
+44 (0)20 7664 8172

Richard Carlson, CFA
Autos/Mobility Equipment & Technology Analyst
BMO Capital Markets Corp.
richard.carlson@bmo.com
(212) 885-4060

Joel Jackson, P.Eng., CFA
Fertilizers & Chemicals Analyst
BMO Nesbitt Burns Inc.
joel.jackson@bmo.com
(416) 359-4250

Peter Sklar, CPA, CA
Auto Parts & Retailing/Consumer Analyst
BMO Nesbitt Burns Inc.
peter.sklar@bmo.com
(416) 359-5188

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BMO Capital Markets

Contributors

KIMBERLY BERMAN
Special Projects Analyst
BMO Nesbitt Burns Inc.
kimberly.berman@bmo.com
(416) 359-5611

JARED DZIUBA, CFA
Oil & Gas Analyst
BMO Nesbitt Burns Inc.
jared.dziuba@bmo.com
(403) 515-3672

COLIN HAMILTON
Global Commodities Analyst
BMO Capital Markets Limited
colin.hamilton@bmo.com
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JOEL JACKSON, P.ENG., CFA
Fertilizers & Chemicals Analyst
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joel.jackson@bmo.com
(416) 359-4250

PETER SKLAR, CPA, CA
Auto Parts & Retailing/Consumer Analyst
BMO Nesbitt Burns Inc.
peter.sklar@bmo.com
(416) 359-5188

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Note: This report was reviewed by a materials chemist to ensure the accuracy of the science cited within.

The Lithium Ion Battery and the Electric Vehicle Market → The Science Behind What You Can't See

The purpose of this report is provide investors with a deep understanding of one of the major gating issues to electric vehicle (EV) adoption → the current state of lithium ion battery electrochemistry. When we surveyed what was being written on the EV space we found that there was a major thought vacuum around the understanding of the internal workings, the design limitations, and the implications of various chemistry alternatives within a lithium ion battery cell. At some level, the development and evolution of this technology is analogous to the refinement and development that took place for the four stroke internal combustion engine (ICE), although likely at an accelerated rate. Although there are other power storage technologies available, the lithium ion battery is what is powering today's electric vehicles and we believe will likely be the dominant technology for the next 5-10 years.

Cutting the Gordian EV Battery Knot

Lithium ion battery chemistry is very complicated and understanding the design challenges, limitations and trade-offs OEMs face is necessary to put EV adoption rates into context. This report should serve as a basis to help loosen the Gordian Lithium Battery Knot for investors. The velocity of intellectual capital being devoted to the space is increasing, and ultimately it is reasonable to expect major advances, but at this point the indications are that battery development is nowhere near adhering to Moore's Law. In addition to a deep dive into battery chemistry and battery design, we provide a deeper and broader understanding of EV adoption around the world. Finally, we leverage a core BMO competency in resources to tie the implications of battery chemistry and global EV developments into a discussion around not only direct commodity inputs into the battery, but also how we view the impact on global oil demand.

All EVs today are powered by some form of a lithium ion battery and the internal chemistries differ across OEMs. We believe that in order to increase EV adoption, battery costs have to decrease and range (energy density) has to increase, while ensuring safety (thermal stability). The lithium ion battery formulation NMC811 (8 parts nickel, 1 part manganese, 1 part cobalt) currently has the most industry development focus. The reason behind this push is that increasing nickel content will increase vehicle range and decrease the need for scarce and expensive cobalt. As an energy source for EVs, the NMC811 formulation is considered to be a key factor to getting the battery costs to the ~$100/kWh needed to achieve ICE parity in the absence of subsidies.

Our analysis of the battery chemistry indicates that there are important challenges in achieving the NMC811 formulation given the instability that is created with increasing nickel content. Essentially, getting rid of cobalt, or even reducing it, is not so simple. We believe, in this context, that without the cost and performance of the NMC811 formulation that EV penetration will be consistent with our 10% penetration by 2025.

Bottom Line: BMO's global view for a **10% EV penetration rate (6% BEVs, 4% PHEVs)[1] by 2025**, and for the **nickel-enriched lithium ion battery to become a dominate technology**. However, the battery industry's move to reduce cobalt content (i.e., NMC811) due to costs could prove difficult given that **cobalt of ~20% stabilizes nickel in a way that ensures functionality**.

[1] BEV = Battery Electric Vehicle; PHEV = Plug-In Hybrid Electric Vehicle

Top 5 Proprietary Takeaways:

1. **NMC811 Lithium-ion Battery Has Technological Risk** → Based on our detailed work on battery chemistry, we believe the consensus view that the next generation lithium ion battery formulation NMC811 (8 parts nickel, 1 part Manganese, 1 part Cobalt) is readily achievable is optimistic. We believe it will be more technically challenging to develop, which impacts some of the more optimistic lithium ion powered EV adoption forecasts. In terms of lithium-ion battery powered EVs, the NMC811 formulation is likely considered a key factor in achieving cost parity with the internal combustion engine (ICE) and increasing the energy necessary to reduce consumer range anxiety. **Implication:** Battery costs may not come down as fast as many have predicted and these findings reinforce our belief that the current and near-term state of the technology is consistent with our 10% penetration forecast by 2025.

2. **The Market Underappreciates the Challenges to Advancing Lithium Ion Battery Chemistry** → We believe the market greatly underappreciates the complexity of the internal workings of the lithium ion battery and the performance trade-offs faced by battery designers that limit the pace of technology development in the near term. **Implication:** There may be other technologies that supplant the current lithium ion battery at some point, but there has been significant ramp in intellectual capital and capital investment in this technology, and the long-term value of innovation is likely underestimated.

Battery chemistry is complex...

...but understanding it is necessary...

... to appropriately evaluate the gating issues to EV adoption...

...which are key to our forecast for 10% EV penetration by 2025

3. **China Is Leading the Way in EV Demand** → There are 172 car companies in China, including the world's largest EV company, BYD. Environmental imperatives and progressive subsidies geared to supporting better technology, not just EV adoption, have positioned China as the world's hot spot for EV development. **Implication:** Increasing investment, vehicle range, EV variety and charging infrastructure in addition to government subsidies are all important to driving this sector.

4. **Supply and Demand of Key Raw Materials a Significant Factor to EV uptake** → Obtaining supply security of lithium, cobalt and nickel can be challenging. **Implication:** Potential bottlenecks could hamper lithium ion battery production despite increasing economies of scale.

5. **EV Growth ≠ Death of Oil Sector** → Our collaborative analysis reveals that EV growth and oil demand are not mutually exclusive. **Implication:** Both industry segments offer a lot of upside over the next five years.

For more information about why we believe that EV growth and oil demand are not mutually exclusive, please read Jared Dzuiba's report, "*Of EVs and Oil Demand*," published (February 20, 2018).

Report Synopsis

The Technology – Challenges of Battery Chemistry

Battery chemistry is very complex, but understanding it is key, as developments inside the battery will impact the performance characteristics that will drive the adoption of EVs and power storage in general. The techniques to optimize cell design, such as packing density and battery structure, have advanced to a point where there is little room for improvement; therefore, the industry is largely focused on changing the internal electrochemistry (improving the cathode, anode, electrolyte, etc.).

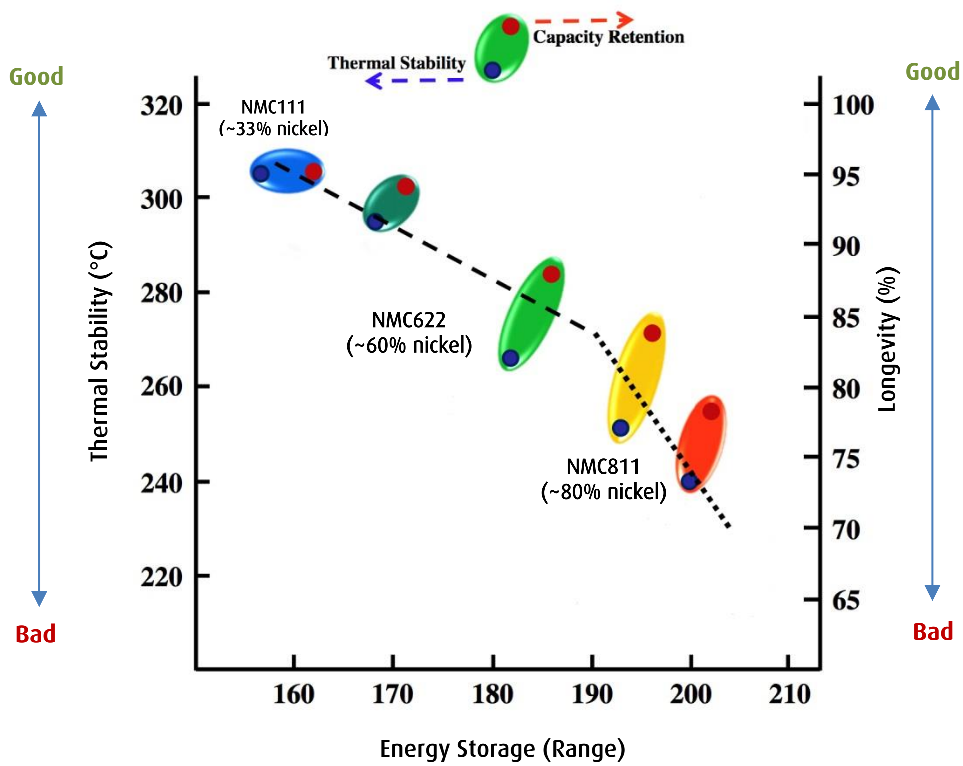
Nickel content may increase range, but it is at the expense of thermal stability and longevity

Value of innovation in decreasing battery costs has been greatly underestimated

In this report, we are focusing on the internal workings of the lithium ion battery and the materials used in the NMC cathode. Continued technology development inside the battery will be the key to achieving lower manufacturing costs, higher energy density, longer range, better temperature tolerances, faster charge rates, lower replacement costs, better battery life, and safety. We believe that these factors need to be addressed at the electrochemical level to ensure higher levels of EV adoption. The industry is particularly focused on the cathode because it represents 22% of the battery cost and is a critical component to increasing vehicle range. Specifically, it cannot hold as many lithium ions as the anode and is essentially the main limiting factor to battery performance.

Our deep dive into the lithium ion battery chemistry in this report concludes that **there are significant risks involving the much-touted NMC811** (8 parts nickel/1 part manganese/1 part cobalt) lithium-ion battery formulation, mainly high technological and patent risk:

- As nickel content increases, the battery becomes increasingly unstable
- The formulation loses its capacity sooner (i.e., cannot hold a charge as long as other formulations)
- *NMC811 is challenged with complicated patent ownership*
- Lower charge rate. Tesla uses an alternative NCA battery chemistry in its cars because it can be supercharged, but manages the inherent instability through an expensive battery management system to keep the system in check this is why a Tesla won't let a driver run successive "Ludacris Modes" without a cooling off period.



See note.[1]

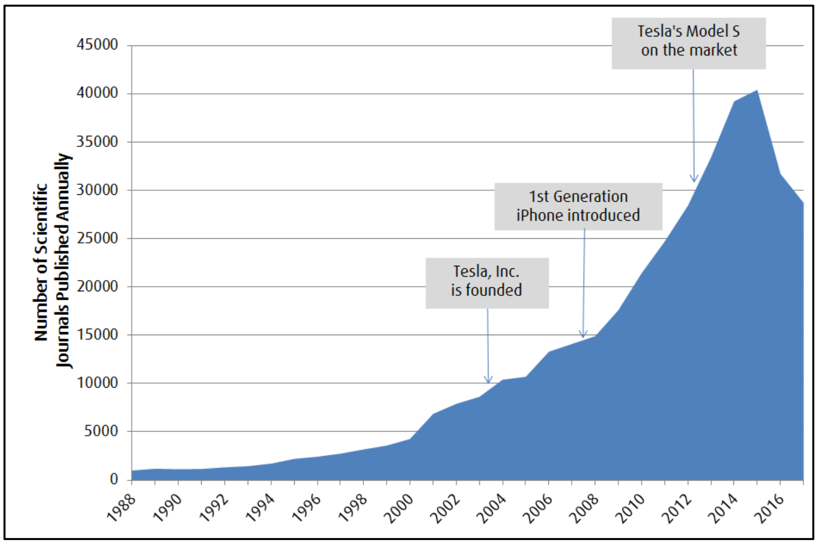
There is likely to be continued reliance on scarce lithium ion battery ingredients such as cobalt, meaning that battery costs may not come down as fast as many have predicted. The industry is

[1] Reprinted (adapted) from Journal of Power Sources, 233, Noh H., Youn, S., Yoon C. and Sun, Y. *Comparison of the structural and electrochemical properties of layered $Li[Ni_xCo_yMn_z]O_2$ (x=1/3,0.5,0.6,0.7,0.8and 0.85) cathode material for lithium-ion batteries.* p.121-130, 2013, with permission from Elsevier.

expecting that the NMC811 formulation will be a key driver in significantly cutting the current $200/kWh costs. We see risks to this happening as increasing nickel content leads to thermal instability and lower capacity retention.

Battery lifespan shortened by continually supercharging. Continually supercharging a lithium ion battery damages the anode, increases structural disordering of the cathode and leads to battery degradation. This means that the lifespan of the battery is shortened. Even Tesla's onboard computer will slow the fast charging process if supercharging is used too often, similar to how Apple slowed older phones to use less power.

The lithium-ion battery – better performance and lower production costs on the horizon. For the foreseeable future the lithium battery is likely the battery technology platform that will see the most development and deployment. We conclude in this report that there are near-term design parameter trade-offs in battery design (chemistry) that could limit adoption. **However, the long-term value of innovation has been greatly underestimated in most cost models.** With the explosion of R&D investment, there will likely be better performance and lower production costs.



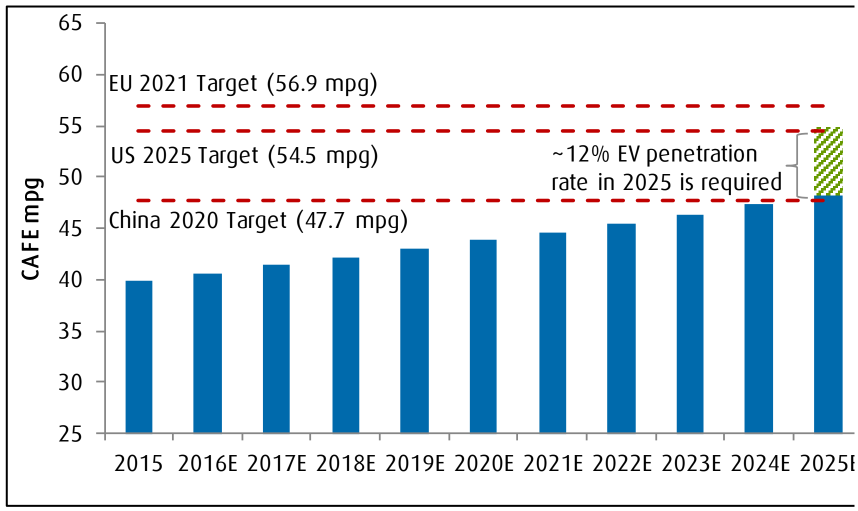
Source: BMO Capital Markets

EV-ICE cost parity is also important to EV adoption. Given the narrowing EV-ICE cost parity, cost alone <u>will not</u> be the main gating factor to EV adoption. We believe that the manufacturing cost savings will equal the offset of the eventual end of subsidy programs. Based on our models and industry sources, we expect that battery costs will decline from ~$200/kWh to $100-125/kWh by the next decade. Specifically, achieving a battery cost of ~$100/kWh would lower the sticker price of an EV by a few thousand dollars (battery costs account for one-third the cost of a BEV), which accounts for a large portion of the subsidies paid by governments.

Cost improvements from economies of scale. We believe that in the near term, cost improvements will likely come from economies of scale. Gigafactories and vertical integration including the direct source of raw materials will likely drive costs rather than battery design. However, targets of $100/kWh vs. current costs of $200/kWh **will only occur with major advances in battery technology chemistry driving the rest of the savings.**

EV Adoption Is Also Dependent on the Following 5 Factors:

1. **EV adoption is necessary to meet environmental regulatory targets.** We estimate that ICE fuel efficiency improvement rates would have to effectively double in order to meet environmental standards without help from much greater EV adoption. We do not see this as a possibility and see increasing EV penetration as inevitable. In our models, global EV penetration would need to reach ~12% in order to comply with environmental regulatory targets by 2025. Given the current state of the battery development, we believe that a 10% EV penetration rate is reasonable given the current constraints on battery chemistry and the supply chain to meet the current formulation.



Note: The 12% penetration rates assumes China, Europe, U.S., Canada, Japan and South Korea (76% of the global car market) reaches ~55mpg fleet average and ICE fuel efficiency grows at historical rate.

Source: US EPA, EC, ICCT, BMO Capital Markets

2. **Better temperature tolerances.** Lithium ion batteries are temperature sensitive and the operating window is narrower than advertised. Increased capacity fade from loss of active lithium and electrode materials causes a reduction in power density. This reduced cycle performance (i.e., charging/discharging) slows down the electrochemistry (particularly the charge transfer kinetics), increases the risk of lithium plating, and causes extensive resistance. Lithium plating causes deposition of metallic lithium on the graphite anode and is a precursor to thermal runaway. Charging repeatedly in cold weather significantly reduces the lifespan of the battery. Batteries are happiest in a climate like California.

3. **Increased EV adoption for local commute.** As it stands, BEVs are ideal for city driving in the course of a day's travel and charging overnight at home. Further development will likely improve some of the gating factors noted above, but the issues are far from simple. But in Norway, 42% of new sales were EVs in 2017—why? In Norway, 85% households have two or more cars and an electric model is only one of them. The typical EV driver is a middle-aged father using an EV for the morning commute.

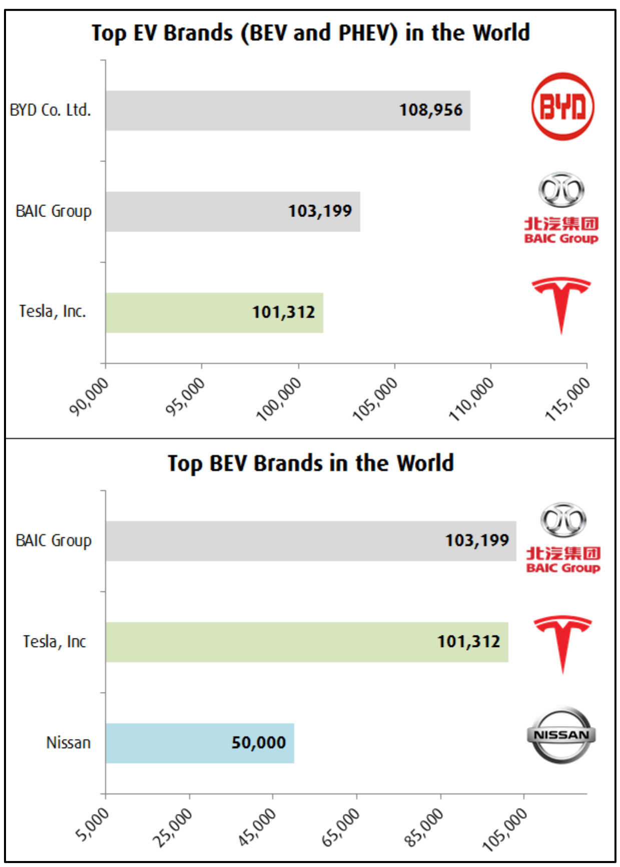
4. **Supply chains of key battery raw materials driver/constraint of EV penetration.** We believe that a 10% penetration by EVs in the global car industry will represent a significant shift in the supply chains of battery raw materials. This is an important consideration since materials need to be qualified four to five years ahead of car launches. Supply chains of key materials such as lithium, nickel, and cobalt will have a significant impact on projected EV market penetration rates. Battery manufacturers have and will continue to

design batteries based on the cost and availability of key commodities. This is yet another reason why the trend has been to improve the current chemistries from a capacity, safety, and cost perspective.

5. **EV adoption to meet emissions reduction goals.** Emissions reduction goals are likely the key drivers of adoption over the near term given the technology hurdles outlined above. The use of light duty vehicles accounts for 16% of emissions, which will put pressure on automobile supply chains and consumer choices. Policy instruments have already been successful in setting fuel efficiency standards and creating campaigns to increase public awareness about road pollution (i.e., effects on health). The strategy here is clear — increasing the number of EVs on the road has been deemed necessary for environmental compliance.

The EV Landscape – China Leading the Way

Growth of the global EV market is led by China. With progressive subsidies, penetration targets, investment, and the number of manufacturers, China has been leading the charge. Tesla might have the highest brand recognition, at least in North America, but Chinese manufacturer BYD (8.25% owned by Berkshire Hathaway) is the world's largest EV company and battery manufacturer. We believe China's lead can be attributed mainly to the following factors. China has 40% of the world's EV car stock and 30% of global sales over all. Over 600,000 units (BEVs, PHEVs and straight hybrids) were sold in 2017, up 71% from 2016.



Source: wattev2buy, BMO Capital Markets

Stiff competition in China but regulations limit foreign brands. China has over 172 companies competing in the automotive space and regulations limit foreign brands. Chinese regulations favour domestic OEMs, such as BYD and Geely, and state-owned entities. Due to regulations, foreign brands on their own account for only 4% of the EV market, with Tesla garnering half of that. Therefore, many brands (GM, Ford, etc.) form partnerships with Chinese companies.

Chinese incentives focused on EV-ICE cost parity. Starting in 2018, China has been trying to incentivize certain performance characteristics from EV manufacturers rather than simply requiring vehicles to be classified as electric propulsion vehicles. Instead, China's incentives for manufacturers focus on getting EVs to be cost competitive with ICE propulsion.

Required EV production thresholds. In September 2017, China tweaked its subsidy program by increasing minimum battery capacity from 90Wh/kg to 105Wh/kg. This push aligns automakers with the country's overall goals as they will have to ensure at least 10% of their fleets are EVs in 2019, which increases to 12% in 2020. Therefore, China represents a key variable to our EV penetration estimates as it is expected to make up about half of all global EV sales in coming years.

Some U.S. EV start-ups receiving substantial capital from China. We have also seen several U.S. start-ups that have received substantial capital from China to introduce new EVs on the market. These include California–based Lucid Motors (formerly Atieva), Detroit Electric Inc., and Faraday Future (a subsidiary of LeEco).

Report Framework

The growth in the electric vehicle market could be hampered by a number of challenges. We address these broad themes in five key sections (click on title for link):

We define the kinds of vehicles in the EV category and lays out the reasons (societal, governmental, disruptive companies, etc.) for the dramatic increase in the market.

We discuss the science behind the lithium ion battery and takes a quick look at the current chemistries on the market and the expected improvements on the horizon that will enable EV uptake.

We go into considerable detail about the cathode chemistries in the lithium-ion batteries currently on the market. Namely, we delve deeply into the scientific reasoning behind our skepticism behind the NMC811 chemistry, which is being touted as the "next big thing," as well as why the cellphone battery chemistry can't be used in electric vehicles.

We discuss the effects of climate on battery performance, which is the biggest impediment to mass market penetration, and the challenges with the charging infrastructure.

We incorporate analysis from our Fertilizers and Chemicals analyst, Joel Jackson, and our Commodities Analyst, Colin Hamilton, to address the supply and demand constraints involved in the key raw materials (lithium, cobalt and nickel) required for the lithium ion battery industry.

The Battlegrounds – The Many Ways to Invest in the EV Space

We also present what we see as the four key battlegrounds to increase EV adoption, which we weave into our five-part report framework summarized above (click on title for link).

The largest EV markets in the world are China (~47.9%), Europe (~29.5%) and the U.S. (~22.6%). We discuss the leading players in the market and detail the fast-paced nature of these evolving markets, which are very different from one another.

Battery companies supply the most crucial component to the EV industry with respect to improving the technology and becoming part of the lithium battery revolution. Over the past couple of years, we have seen tremendous competition between key battery suppliers — especially on the cathode side. Whether they are at the benchtop level or are niche players (e.g., motorcycles), these companies have been furiously positioning themselves to be acquired or be the next LG Chem.

This race is mostly predicated on increasing the range of the battery, but we believe it also involves growing a larger, more homogenous public charging infrastructure and tackling the fussy temperature issues or the decreased range of many models.

The final battleground will involve ensuring long-term supply of key raw materials such as lithium, cobalt, and nickel. Volkswagen's recent well-publicized failure to secure a long-term cobalt supply highlights a key constraint in this market.

Part I – The Increasing EV Market – 10% Penetration by 2025

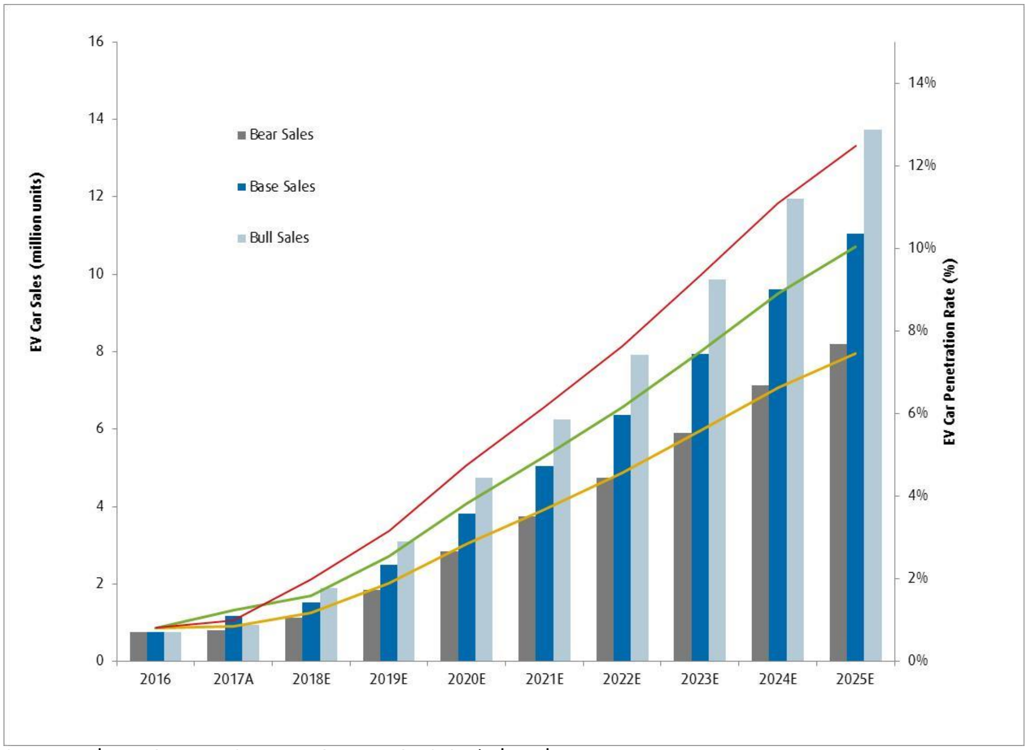
Our base case of 10% penetration by 2025 looks fairly reasonable given OEM targets and tighter regulations

Although it is difficult to accurately predict the pace of transition from fossil fuel-powered ICEs (internal combustion engines) to EVs (electric vehicle), **we believe our base case estimate of a 10% penetration rate by 2025 (a ~30% CAGR) is very reasonable**. That number could easily be 5% or 20% in the next seven years compared to the 1.2% rate (less than a million cars) seen in 2017.

Based on our conversations with battery industry sources, 10% actually seems very difficult to achieve from a supply chain standpoint, but it is below aggregate automobile OEM sales targets of ~14.3% EV penetration in 2025. By many accounts, this estimate is deemed aggressive while to others, it is too conservative. Our assumption of 10% is based on a penetration of 6.6% for BEVs (battery electric vehicle) and 4.4% for PHEVs (plug-in hybrid electric vehicle) for a total of ~11 million EVs sold globally in 2025.

In our bull case, we assume 12.5% EV penetration in 2025 (BEVs 8.2%, PHEVs 5.5%) assuming global environmental targets for vehicle emissions are met. This case also implies ~87% of OEM targets are achieved. In our bear case, we assume 7.5% EV market penetration in 2025 (BEVs 4.9%, PHEVs 3.3%).

Figure 1: We Expect a 10% EV Car Penetration Rate by 2025



Source: Industry Reports, Company Reports, BMO Capital Markets

Figure 2: Our Base Case Assumes a Ramp-up From 1% to 10% EV Car Penetration by 2025

EV Sales Cases	2012	2013	2014	2015	2016	2017A	2018E	2019E	2020E	2021E	2022E	2023E	2024E	2025E
Total Vehicle Sales (IHS)			86.9	88.7	92.21	93.84	95.20	98.01	99.86	101.68	103.54	105.69	107.78	109.93
Bear Sales														
Bear Rate					0.8%	0.9%	1.2%	1.9%	2.8%	3.7%	4.6%	5.6%	6.6%	7.5%
BEV Bear	0.06	0.11	0.19	0.33	0.47	0.48	0.68	1.11	1.70	2.24	2.84	3.54	4.28	4.92
PHEV Bear	0.060	0.092	0.134	0.222	0.287	0.32	0.45	0.74	1.14	1.50	1.89	2.36	2.86	3.28
EV Sales (million units)	0.12	0.20	0.32	0.55	0.75	0.80	1.13	1.86	2.84	3.74	4.73	5.89	7.14	8.20
Base Sales														
EV Car Penetration Rate (%)			**0.4%**	**0.6%**	**0.8%**	**1.2%**	**1.6%**	**2.6%**	**3.8%**	**5.0%**	**6.2%**	**7.5%**	**8.9%**	**10.0%**
BEV	0.06	0.11	0.19	0.33	0.47	0.70	0.91	1.50	2.29	3.02	3.82	4.76	5.77	6.62
PHEV	0.06	0.09	0.13	0.22	0.29	0.47	0.61	1.00	1.53	2.01	2.55	3.17	3.85	4.42
EV Car Sales (million units)	**0.12**	**0.20**	**0.32**	**0.55**	**0.75**	**1.17**	**1.52**	**2.50**	**3.82**	**5.04**	**6.37**	**7.94**	**9.61**	**11.04**
Bull Sales														
Bull Rate					0.8%	1.0%	2.0%	3.2%	4.8%	6.2%	7.6%	9.3%	11.1%	12.5%
BEV Bull	0.06	0.11	0.19	0.33	0.47	0.56	1.13	1.86	2.85	3.76	4.75	5.92	7.17	8.23
PHEV Bull	0.06	0.09	0.13	0.22	0.29	0.38	0.76	1.24	1.90	2.50	3.17	3.94	4.78	5.49
EV Sales (million units)	0.12	0.20	0.32	0.55	0.75	0.9	1.9	3.1	4.7	6.3	7.9	9.9	11.9	13.7

Source: Industry Reports, IEA, BMO Capital Markets

Our current estimates include BEV and PHEV unit sales

Our definition of EVs includes BEVs (battery electric vehicle) and PHEVs (plug-in hybrids). In our models, we layer on electric bus (E-buses) forecasts separately (though buses are a relatively small component of our total estimate). For now, we are not considering straight hybrids (HEVs) such as the Toyota Prius or Kia's Niro – as in our base case 10% EV penetration – as HEVs do not use the lithium ion battery technology at this time. However, many announcements from countries and automakers tend to group all three together.

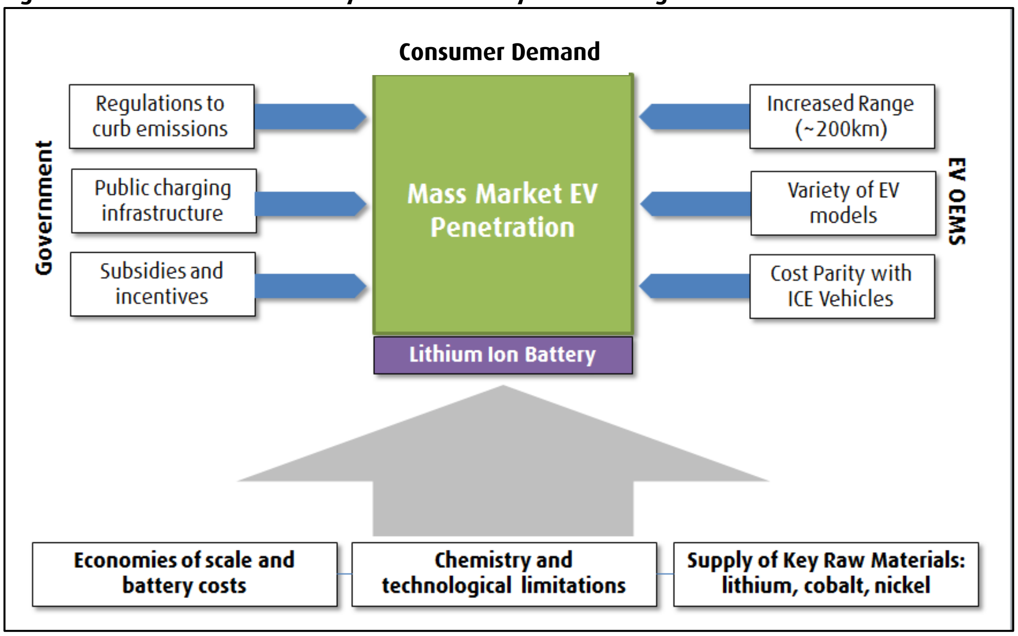
- **Battery Electric Vehicle (BEV).** These vehicles are powered solely by electricity from an on-board battery pack that is charged by plugging into the grid and do not have a backup energy source. Examples include the Nissan Leaf and Tesla's Model S. The average battery pack size and the electric range of BEVs on the market today are ~40kWh and ~230km (150 miles), respectively, though ranges have been improving over time.

- **A Plug-In Hybrid Electric Vehicle (PHEV).** These vehicles have both a gasoline engine as well as a battery pack, which is recharged with normal electric outlets. PHEVs do not run on electricity over their full range and once the battery capacity is used, the ICE engine kicks in. Essentially, the internal systems are designed to use the lowest fuel consumption to meet power demands. For example, the system may switch on the engine in cold weather, during heavy acceleration, at high speeds or other challenging circumstances. PHEVs can be Parallel (ICE directly connected to the wheels to provide propulsion when needed) or Series (only uses the ICE to generate electricity to recharge the battery). The average battery pack size and electric range of current PHEV models on the market today is ~12kWh and ~40km (25 miles), respectively.

- **Hybrids (HEV).** Hybrids (sometimes referred to as straight hybrids) primarily rely on a traditional engine supplemented by an electric motor that provides some level of propulsion, mainly during light acceleration. The motor either recharges the battery pack by capturing energy otherwise lost during braking or uses an electric generator when the ICE engine is in operation. HEVs do not "plug in" to outlets and generally use a nickel-metal hydride battery (NiMh). The average battery pack size of current HEV models on the market today is ~1kWh. While hybrid OEMs are starting to adopt lithium-ion batteries, they are not scaled to the same extent as BEVs and PHEVs and therefore we do not include them in our models. However, market penetration of HEVs does impact our market balance analysis of nickel summarized in Part V in this report and is a key factor in our view of the impacts of EVs on the oil industry.

While our assumptions are founded on the EV definition that includes BEVs and PHEVs, they are also based on **the confluence of many societal, economic, political, technological and environmental complexities** that together are propelling electric cars to the forefront of the auto industry. Sure, the regulatory push is a significant factor, and we address this in greater detail next, but there are also other factors such as increasing infrastructure and the introduction of newer EV models with increased range. However, we believe that the lithium ion battery technology forms the base of this industry and future improvements to battery design will help propel this market even further.

Figure 3: The Confluence of Many Factors Are Key to Achieving Mass Market Penetration



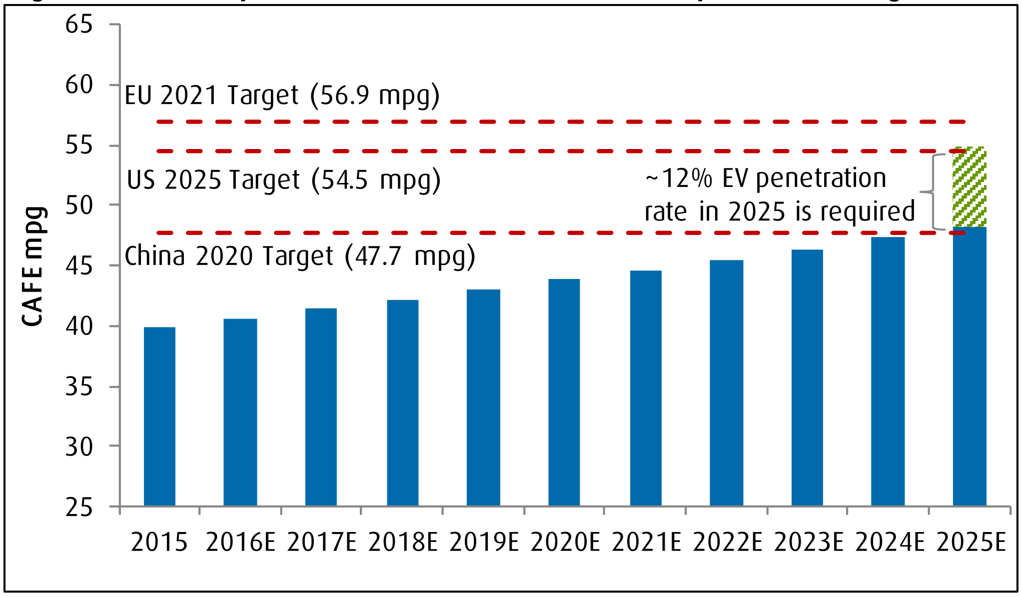
Source: BMO Capital Markets

1. Regulatory Pressures to Reduce Emissions

Pollution from the transport sector is responsible for about 25-30% of global greenhouse gas emissions (GHG). Scientists have shown that burning fossil fuels causes a buildup of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) into the atmosphere causing the climate to change. Many of the agencies such as the Carbon Dioxide Information Analysis Center (CDIAC) and the International Energy Agency (IEA) have forecasted that CO_2 will increase past the 35,000 MMT mark in the coming years. As such, there has been a large international push to ratify agreements such as the Paris Agreement in an effort to curb global emissions.

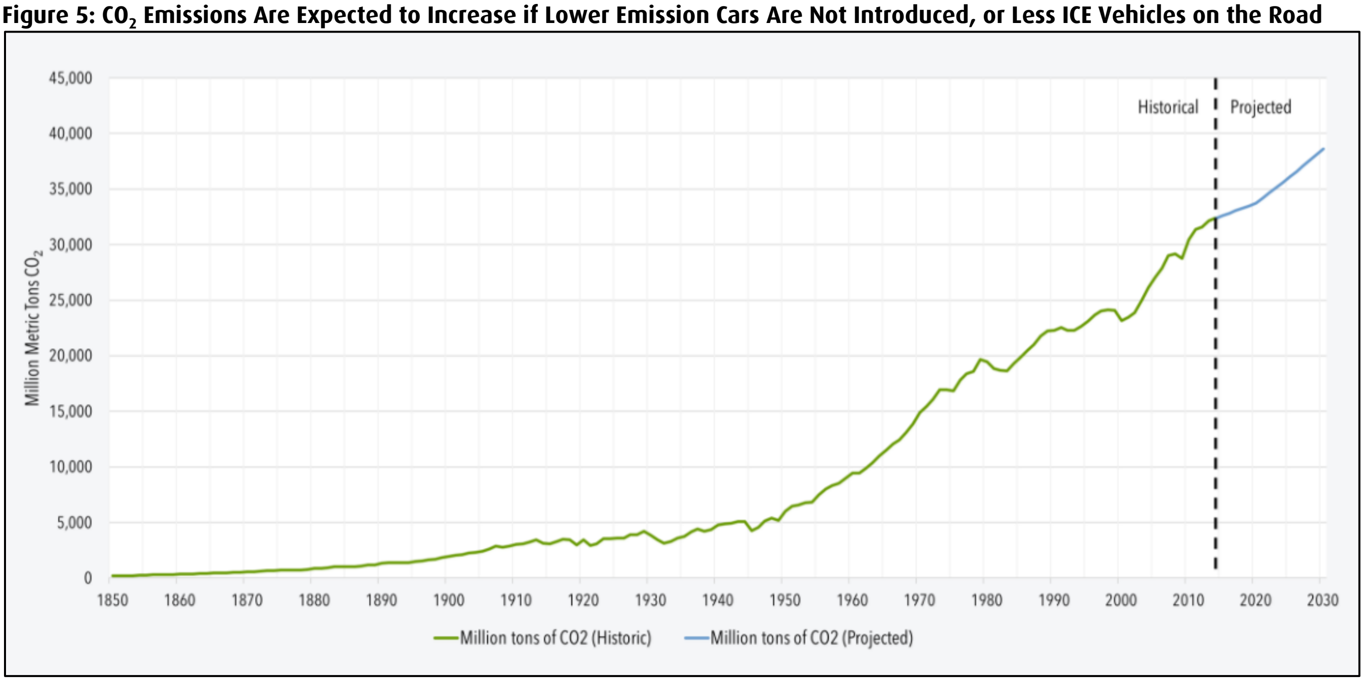
To say that reducing emissions to a sustainable level has been difficult is an understatement. There have been many failed policy attempts (e.g., carbon taxes, the Kyoto Accord, cap and trade systems, etc.). Canada provides a good example. While Canada has ratified and remained in the Paris Agreement, it is unlikely that emissions targets will be met given the current state of its climate change policy as well as past difficulties in meeting previous targets. Despite the best intentions, emissions keep going up. Similar to the U.S., Canadians remain deeply divided over how to move away from the country's fossil fuel legacy. We see a kind of "push and pull" happening at the policy end in North America as well as in other countries.

Figure 4: We Currently Model a ~12% EV Penetration Rate Is Required to Meet Targets



Note: The 12% penetration rate assumes China, Europe, US, Canada, Japan and S. Korea (76% of the global car market) reach ~55mpg fleet average and ICE fuel efficiency grows at historical rate.
Source: US EPA, EC, ICCT, BMO Capital Market

Figure 5: CO_2 Emissions Are Expected to Increase if Lower Emission Cars Are Not Introduced, or Less ICE Vehicles on the Road

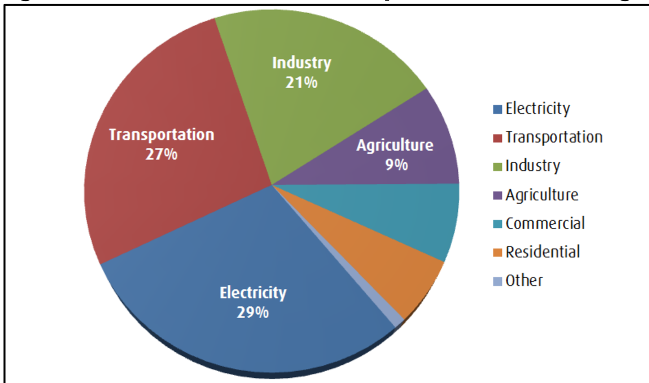


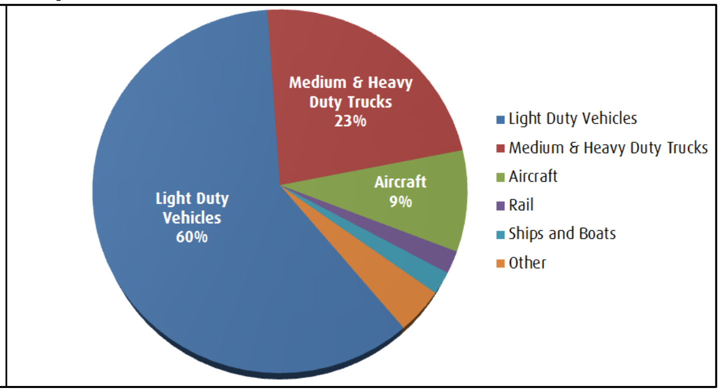
Source: Centre for Climate and Energy Solutions (C2ES)

It is a no-brainer for governments to support the EV industry as increasing market uptake reduces emissions

The transportation sector is a significant contributor to these increases and therefore, part of the overall strategy includes various ICE phase-out plans. This makes sense to us given that the technology is there and that *16% of emissions come from light duty vehicle use*. This in turn will put pressure on automobile supply chains and consumer choices. Policy instruments have already been successful in setting fuel efficiency standards and increasing public outcry by creating awareness about road pollution issues (i.e., effects on health). **The strategy here is clear — increasing the number of EVs on the road has been deemed necessary for environmental compliance.** While there has been research regarding emissions generated at the battery manufacturing level, at this juncture, we are focusing on the ability of EVs to reduce emissions at the local level and to curb the debilitating pollution levels rising in urban centres.

Figure 6: 2015 U.S. GHG Emissions by Sector Shows That Light Duty Vehicles Contribute 16% to Overall Amounts





Source: US EPA

Regulatory Policy Trends Used to Promote EV Usage

The main policy trend to accelerate the EV change has been the use of direct subsidies to consumers making the total cost of ownership more in line with an ICE powered vehicle. **We believe that financial incentives are necessary (for now) to ensure reasonable cost parity between EVs and ICEs.** All major EV markets have some form of financial support from the government, as well as various non-financial incentives, and policy initiatives to promote investment in public charging infrastructure. As the EV market grows, however, we expect financial incentives will eventually be phased out, potentially offset by declining battery costs.

Moving toward zero emissions – *i.e., phasing out ICEs* – in Europe

- *France* announced plans on July 6, 2017, to completely ban all sales of petrol and diesel vehicles by 2040, as part of a plan to try to reach the country's targets under the Paris climate accord. Furthermore, the country would provide financial assistance for less-wealthy households to replace older ICE vehicles with EVs.

- *The U.K.* followed France's lead and made similar announcement two weeks later adding that all cars will need to have zero emissions by 2050. To date EVs in the UK make up ~1.5% of sales, and 0.25% of stock.

- *Norway* has set a target of allowing only BEV or PHEV sales by 2025. The country has been the international role model for regulations, incentives and greening energy infrastructures. Norway currently has the highest per capita number of BEVs on the road (>1,000 units), and last year, 40% of new car sales were BEVs or hybrids. We believe that Norway will continue to be the beacon for EV adoption around the globe.

- *The Netherlands* is currently in the process of imposing a similar ban on the sales of new petrol and diesel cars starting in 2025 — the motion has already passed in the lower court. In 2016, EV sales were 6.4% of auto sales representing 1.6% of the vehicle stock in the country. Those numbers changed to only 2% of auto sales, but that is because regulations are favouring BEVs over PHEVs. The reality is that BEVs increased to 1.95% from 1.05% in 2016 of new EV registrations while PHEVs continued to decline from 9.19% in 2015 and 4.92% in 2016 to only 0.28% in 2017. This trend aligns with the country's increasing charging infrastructure as it currently has the greatest number of public charging stations (32,120 normal and 755 fast chargers) in Europe.

- *Germany* and *India* are also looking to follow this trend by having all-electric fleets by 2030. However, we believe neither country will be able to green its infrastructure in time to meet emissions targets. Germany does present an interesting conundrum given its aggressive emissions targets and high economic reliance on the large, premium ICE market. BMW does, however, have a considerable amount of the BEV market share with its i3 model claiming 10.8% of the European market and 5.9% of the North American market.

U.S. hasn't shown much interest in ICE phase-out but offers a federal tax credit

- *The U.S.* has not shown much interest in ICE phase out plans at the federal level, but does offer a federal tax credit of up to $7,500. To date, most of the EV promotion has been at the state level with California leading the charge with very ambitious goals. For example, in 2010, the state required automakers to reduce GHG emissions for their vehicles by 2016. However, there was a pull-back on the subsidy program last year as Bill AB-1184, which would have provided US$3 billion in EV incentives over the next decade, was stripped of its funding in September 2017 and altered to direct the California Air Resources Board to produce a case study on EV subsidies by 2019. Despite this, California's initiatives still provide a template for other jurisdictions in North America to follow suit. Given strong public opinion for more environmental regulation and an extension of its cap and trade system to 2030, its new policies will likely strengthen California's environmental vision.

In Canada, provinces provide substantial subsidies, but slow EV uptake is due to low vehicle range and poor performance in low temperatures

- In *Canada*, provinces have followed many of California's initiatives, including providing substantial electric car subsidies. One example is Ontario's Electric Vehicle Incentive Program (EVIP), which provides consumers with incentives in the range of C$6,000-14,000 depending on the battery capacity and vehicle type. In addition, Quebec enacted the Drive Electric Program for Cleaner Vehicles in 2012, which offers subsidies of up to C$8,000, and the program has evolved to include subsidies in the secondary EV market. Quebec has also introduced the only zero emissions mandate. As of now, however, there are only about 15,000 vehicles on the road and the Quebec government is aiming for 100,000 by 2020. This slow uptake exemplifies Canada's lagging EV adoption compared to other countries. While we believe that the lack of a national mandate is contributing to this, there are also a number of technological challenges (low range, poor temperature performance) that have impeded adoption rates both in Canada and in the U.S., which will be detailed later in this report.

- Cities are also following suit as Copenhagen plans to ban gas and diesel powered cars starting in 2019 while other cities such as Barcelona, Los Angeles, and Milan are toying with a ban in parts of their cities by 2030. These initiatives are also driven by efforts to reduce air pollution within urban centres.

Figure 7: Detailed Picture of EV Incentives and Charging Infrastructure of Key Countries

Country	Emission Regulations	ICE Phase Out	EV Financial Incentives	EV Non-Financial Incentives	Charging Infrastructre[1]	Total Chargers Per Capita
China	China VI	New energy vehicles to make up 20% of 2025 sales	◦ Federal subsidy up to ~44,000 CNY (~6,300 USD) and tax exemptions ◦ Regional subsidies of 300-500K CNY for electric buses	◦ Exemption from restrictive license plate auctions ◦ Exemption from congestion charges	◦ 52,778 Public Slow Chargers ◦ 88,476 Public Fast Chargers	◦ 102 per million people
France	Euro 6	Announced on July 6th 2017, ICE ban by 2040	◦ 25% off purchase price per EV ◦ 15% subsidy for companies replacing petrol/diesel vehicles with an EV		◦ 14,407 Public Slow Chargers ◦ 1,904 Public Fast Chargers	◦ 243 per million people
The Netherlands	Euro 6	Announced on Aug 16th 2016, ICE ban by 2025	◦ 20% off purchase price (up to €40,000) per EV ◦ EVs and chargers are partially tax deductible ◦ Reduction on company car taxes ◦ Exempt from road and registration taxes	◦ Free floating parking permits for car sharing companies with EV fleets	◦ 32,120 Public Slow Chargers ◦ 755 Public Fast Chargers	◦ 1,931 per million people
Norway	Euro 6	Announced on June 4th 2016, ICE ban by 2025	◦ No purchase or import taxes ◦ Exempt from 25% VAT for BEVs ◦ 50% reduction on company car taxes ◦ Exempt from road and ferry tolls ◦ Circulation tax exemption	◦ Bus lane access ◦ Free municipal parking ◦ Free electricity for normal charging (3.6kW)	◦ 8,292 Public Slow Chargers ◦ 2,058 Public Fast Chargers	◦ 1,978 per million people
Sweden	Euro 6		◦ Federal grant of up to 40,000 kroner ◦ Circulation tax exemption		◦ 2,363 Public Slow Chargers ◦ 2,370 Public Fast Chargers	◦ 477 per million people
United Kingdom	Euro 6	Announced on July 25th 2017, ICE ban by 2040	◦ Federal grant up to £4,500 for BEVs, £2,500 for PHEVs ◦ Federal grant of additional £3,000 for zero emission taxi ◦ Circulation tax exemption	◦ Exemption from congestion charges ◦ Free or reduced parking in some boroughs	◦ 11,497 Public Slow Chargers ◦ 2,759 Public Fast Chargers	◦ 217 per million people
United States	EPA		◦ Federal tax credit up to $7,500 ◦ State rebate up to $2,500	◦ City parking benefit ◦ Access to HOV lanes	◦ 35,089 Public Slow Chargers ◦ 5,384 Public Fast Chargers	◦ 125 per million people

[1]Based on 2017 charging data from EAFO except for China and U.S. (2016)

Source: EAFO, ICCT, IEA, BMO Capital Markets

2. Increasing Investment in Charging Infrastructure

In the last five years, charging infrastructure has moved the EV subculture of sharing personal chargers to the mainstream with more public charging stations at more locations. **We believe that charging infrastructure is another key ingredient to increasing BEV uptake.**

Norway has been the worldwide leader in developing a wide array of incentives to promote the EV industry and it was recently announced that there are now over 200,000 EVs on the road. An interesting look at the timeline in the figure below shows that these policies were enacted by 2010 before the number of new BEV registrations started to go up. Therefore, there are factors other than regulations alone that contributed to the sudden rise in new EV car registrations.

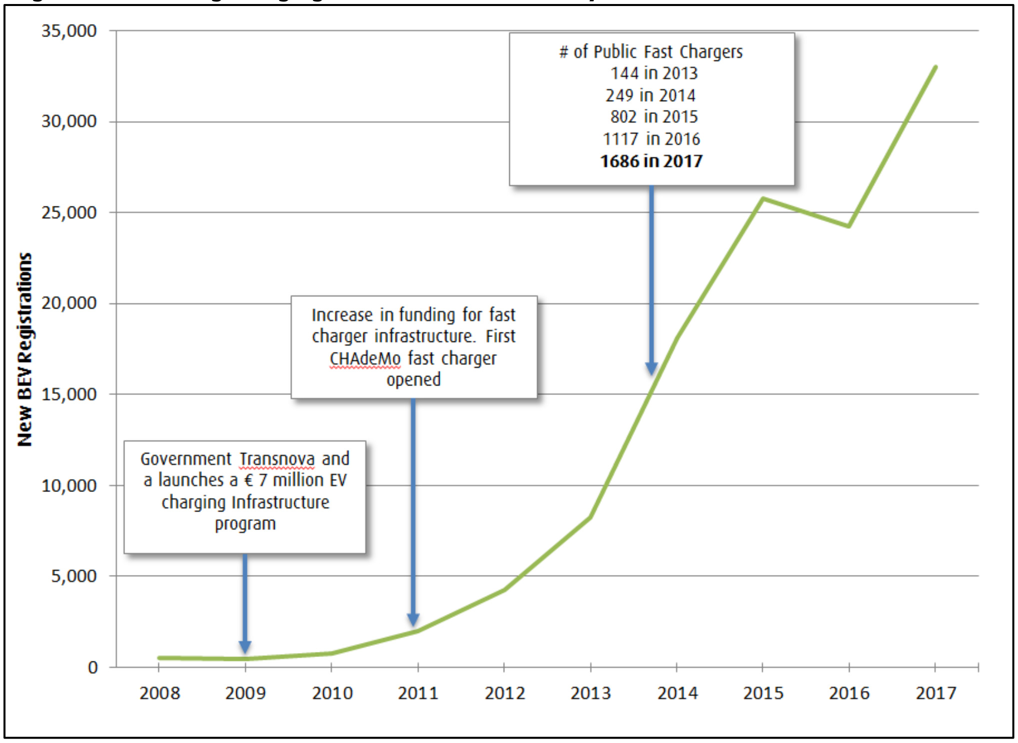
Figure 8: Timeline of Norway's EV Incentives

	Incentives and Tax Reduction
1990	Exemption from registration tax (The ICE vehicle tax is based on height and weight of the vehicle and the taxes on VW Golfs are ~6000€).
1996	Permanent abolishment of import tax
1995	Norwegian Electric Vehicle Association is set up to promote EV interests
1996	Reduced annual registration tax
1997	Exemption from road tolls (costs can range from 600-1000€ per year for commuters)
1999	The introduction of special "EL" license plates coincides with the free public parking.
2000	Reduced company car tax
2001	Zero VAT taxes (ICE vehicles are levied with a 25% VAT on the sales price minus the registration tax)
2003	Access to bus lanes in the Oslo region
2005	Access to bus lanes made permanent, and extended nationwide saving time for BEV drivers during rush hour.
2009	Free access to road ferries.
2013	Weighted tax deduction for PHEVs

Source: Norsk Elbilforening, Figenbaum et al., 2017

As charging infrastructure increased in Norway, the rate of BEV market uptake increased rapidly

Figure 9: Increasing Charging Infrastructure Is Also Key for Mass BEV Penetration



Note: Transnova is a funding program established in 2009 to provide financial benefits to advance solutions to the environmental problems within the transport sector.
Source: Norsk Elbilforening, BMO Capital Markets

While many would rightly suggest that the popularity of EVs in Norway has something to do with the introduction of better, more luxurious models with better range (the Model S was introduced in Norway in 2013), we believe that the rise in high powered public charging stations also plays a key role.

Furthermore, the UK has invested heavily in its public charging infrastructure over the last five years and currently has 11,497 normal chargers and 2,759 high power chargers. With that, the number of new EV car registrations has inched up to 2.9% of total car registrations in December 2017 compared to 1.7% for the same month in 2015 and 2016.

We believe that increasing the number of public chargers on a per capita basis is key to reducing range anxiety and an important factor to promote BEV market expansion.

Different Types of Charging Methods Makes It Much More Complicated

Simply increasing investment dollars into the charging infrastructure is only part of the puzzle. The other part is to try to establish some sort of uniformity. There are currently three main EV charger types. EV charge points are characterized by the power (kW) produced, equating to speed of charge. There are many definitions as some sources refer to four modes rather than three levels and provide different ranges and definitions. However, the ranking from slow to fast charging are the same between all methods.

Here, we are using the rankings and definitions used by the International Council on Clean Transportation (ICCT).

- **Level 1 or 1C - Slow chargers: 120V AC (~15 Amps).** The most common form of charging because it simply means plugging your car into an ordinary household outlet. Charging in this manner is typically done overnight as a full charge can take many hours with *power delivery of up to 1.2-1.8kW.*

- **Level 2 or 2C - Typical household, workplace and public chargers: 240V AC (~30 Amps).** Can fully recharge BEVs in 1-4 hours with *power delivery of 3.6-22kW.* Speeds will depend on the model's on-board charger.

- **Level 3 or 3C - Fast Chargers: 400V DC (~100 Amps).** Fast chargers are designed to provide ~80% charge in ~30 minutes with *varying power delivery of 40-120kW.* Typically found in locations close to highways and strategically within urban areas, fast chargers are the preferred charging stations for Tesla's vehicles.

The issue is that some cars are limited to a charging level that can be accepted. For example, the pre-2018 Nissan Leaf models can only be charged at a maximum of 6.6kW meaning that a fast charger (3C) cannot be used. There are also different fast chargers types, which include CHAdeMO, SAE and Tesla's supercharger – the ability to use each type is dependent on the car type and availability of adapters provided from manufacturers. Tesla is currently the only car that can use all chargers because of its range of adapters while others may or may not be able to adapt to other charging designs. Essentially, fast-charge plugs do not fit all cars and the lack of uniformity (along with uncertain charging costs) needs to be solved at the policy level. A more detailed synopsis is provided in part IV of this report, but for now, the lack of uniformity means an added complication to the end user compared to simply 'filling up' at a gas station.

Figure 10: Types of Fast Chargers Available

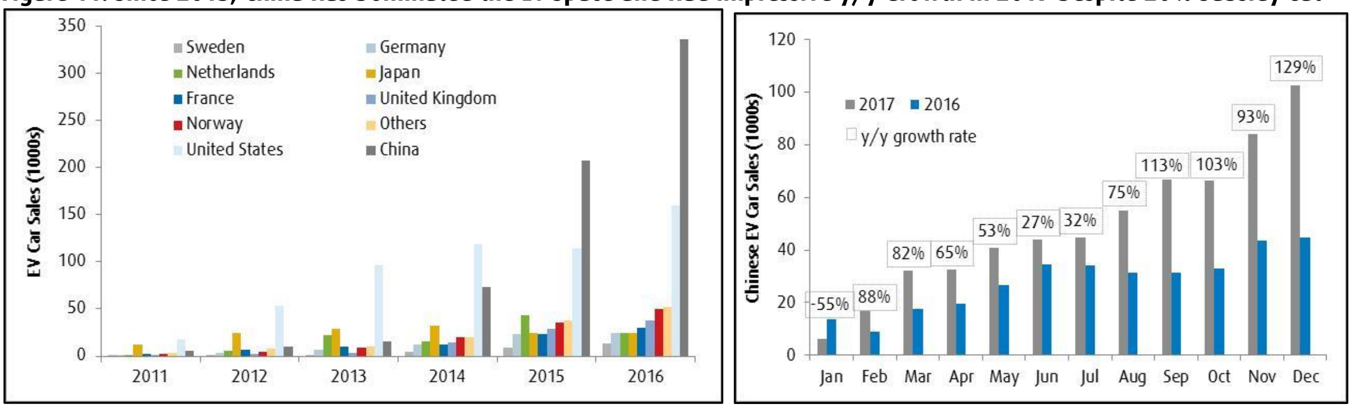
Source: Inside EVs, greentransportation.com

3. China's Very Big Push Into Electrification

China is by far the largest market for EVs in the world, representing 40% of EV car stock (~30% of global car sales overall). China has been actively promoting the EV market and has offered generous subsidies at both the national and local levels through various programs with an end goal of having 5 million EVs on the road by 2020. While there are no current plans to introduce an ICE ban, the sudden growth in Chinese EV sales and interest can be mainly attributed to these subsidies along with a common public interest to reduce air pollution. China's ongoing and difficult-to-manage pollution problem has re-emerged as the country grappled with historic smog levels with

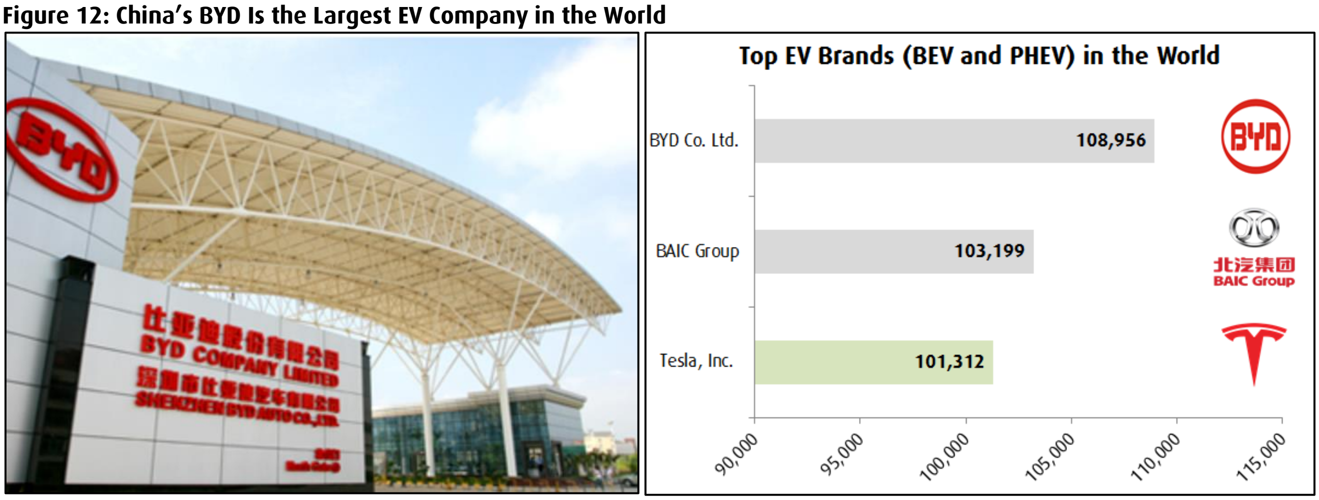
32 cities under 'red alert' last summer due to transport emissions and the industrial use of coal. China has taken an aggressive approach to combat these issues. First, it has adopted a well-drawn strategy to electrify the transport sector. According to the country's emission reduction goals set forth in its first climate change update report released in 2010, BEVs would have to make up 10% of new car sales by 2019 and 12% by 2020. Overall 2020 targets include reducing CO_2 emission by 40-45% 2005 levels, increasing non-fossil fuel consumption to 15%, increasing forest stock volume and coverage by 1.3 billion m^3 and 40 million hectares, respectively, compared to 2005 levels. These initiatives have certainly set the tone for Chinese automakers to become dominate in the EV space. In addition, BYD Co. Ltd and the BAIC Group are the top EV OEMs in the world by unit volume.

Figure 11: Since 2015, China Has Dominated the EV Space and Had Impressive y/y Growth in 2017 Despite 20% Subsidy Cut



Source: IEA, EV Sales Blog, BMO Capital Markets

Figure 12: China's BYD Is the Largest EV Company in the World



Source: BYD, wattev2buy, BMO Capital Markets

Regulations Are Geared Toward Making Better EVs

China's subsidy program is geared toward making better batteries and EVs with longer range

From the beginning, **China set up its national subsidy program with the intention of eventually removing them in a way that would put the onus on car manufacturers to make better EVs that are cost competitive with ICE powered cars.** In fact, China has stated that its subsidy program is expected to be completely phased out by 2020 and subsidy amounts will drop 20% annually. At the end of 2017, it was announced that there would be major changes to the subsidy program starting in 2018. While part of this is due to a crackdown on subsidy fraud, the minimum energy density (battery power/weight) required to obtain subsidies has been increased from 90Wh/kg to

105Wh/kg and the subsidy for EVs with a 100-150km electric range would be eliminated. We believe that there will be more changes like this to come as the 2020 subsidy drop date nears. We view this subsidy strategy as being tailored to incentivize battery manufacturers to improve the range offered by existing technology and OEMs as they must sell EVs to operate in the country.

Figure 13: China's EV Subsidies Until 2017

EV Type	Energy Density Wh/kg	Electric Range	Subsidy Level (¥) 2016	2017
BEV	90-120 Wh/kg	100-150km	25,000	20,000
		150-250km	45,000	36,000
		>250km	55,000	44,000
	>120Wh/kg	100-150km	25,000	22,000
		150-250km	45,000	40,000
		> 250km	55,000	48,000
PHEV	-	>50km	30,000	24,000

Source: ICCT

Figure 14: What We Know So Far About the New Subsidy Rules From 2018 to 2020

EV Type	Energy Density Wh/kg	Electric Range	Subsidy Level (¥) 2018	2019 (e)	2020(e)
BEV	105-140 Wh/kg	100-150 km	-	-	-
		150-300 km	28,800	23,040	-
		300-400 km	55,000	44,000	-
		>400 km	55,000 +	44,000 +	-
	>140Wh/kg	100-150km	-	-	-
		150-250km	150-300 km	40,000	-
		> 250km	300-400 km	48,000	-
			>400 km		
PHEV	-	>50km	30,000	24,000	

Source: Cleantechnica

While China plans to phase out monetary subsidies, it will be replaced with a quota system for OEMs

While there are also some local subsidies, that have caused some impediments to cars produced in other provinces, the Chinese government has indicated plans to stop these protectionist policies. It has also been reported that a quota system will replace its subsidy program in 2020 and beyond. Despite these changes, we believe that China will continue to push for the transition from ICE cars to EVs in a number of ways that will also include increasing infrastructure and providing OEMs incentives to make the switch.

The Chinese Market Is Key to Our Forecasts

China is key to meeting our 10% penetration estimate and we expect it to account for half of all future global EV sales

EV sales grew substantially in 2017, especially in the last quarter, despite a 20% reduction in financial EV subsidies from 2016-2017 to consumers this year, meaning that it's not just subsidies pushing the case. China also introduced a credit score program regulation in September 2017, which requires automakers to produce a certain threshold of what the government deems "New Energy Vehicles" (BEVs and PHEVs) or be subject to significant financial penalty (OEMs may buy credits from others). This push aligns automakers with the country's overall goals as they will have to ensure that their fleets are at least 10% EVs in 2019 and 12% EVs in 2020. Therefore, **China represents a key variable to our EV penetration estimates as it is expected to make up about half of all global EV sales in the coming years.**

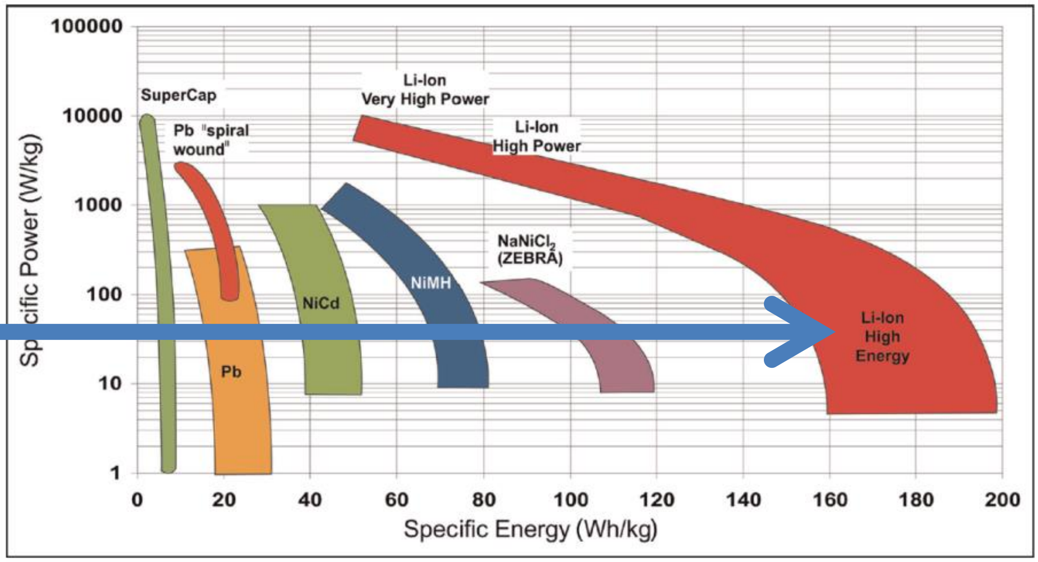
Our models show that total 2016 EV sales in China were ~340,000 units, and 2017 sales grew 74% to ~591,800 units. Despite recent impressive growth, China will need to dramatically scale up its EV manufacturing in the next three years to achieve the Chinese OEM combined target of 2.0 million in unit sales by 2020 and 7-8 million by 2025.

4. Battery Technology Now More Robust and Expected to Improve

The commercialization of the lithium ion battery (LIBs) has provided the thrust for the electromobility market to take off as it offers more range between charges than its predecessors while providing the power density needed to compete with ICE vehicles. Commercialized in the 1990s by Sony, LIBs have clear technological advantages over the first and second generation rechargeable batteries such as nickel cadmium (NiCd) and nickel-metal hydride (NiMh) due to their higher specific power and high specific energy (capacity). The NiMh has been the battery of choice for traditional hybrids, such as the Toyota Prius. However, the battery's initial foray into the BEV market (i.e., GM's EV1 circa 1996-1999) was a failure due to its size, weight, limited range (mileage) and excessive self-discharge (loss of energy when not in use).

↑ specific energy =
↑ capacity =
↑ specific energy =
↑ range (or mileage)

Figure 15: The Lithium Ion Battery Wins With its Higher Capacity = Increased Range



Budde-Meiwes *et al.* (2013). *A review of current automotive battery technology and future prospects.* J. Automobile Engineering; 227(5):761-776.
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LIBs provide the same energy as traditional batteries but at:

- half the size & weight
- higher voltages
- low self-discharge rate
- higher cyclability

Given the higher specific energy and specific power, along with a lighter weight principally due to higher nominal voltage of LIBs, companies such as Tesla were motivated to adapt the technology for use in the automotive industry. Compared to the nickel-metal hydride (NiMh) battery, LIBs provide the same energy *at half the size and weight* with much higher voltage. For example, Walmer (2015) calculated that a 350V NiMh battery would require about 292 cells while a lithium ion battery with the same voltage would require only 98 cells. LIBs also have a much better cycling life (i.e., charge and discharge) compared to other rechargeable chemistries on the market and can reach thousands of cycles before needing to be replaced. Part of this is due to the *lack of a memory effect*. For example, if a NiCd battery were charged after being only partially discharged, it would lose capacity because it would begin to mirror that partial range.

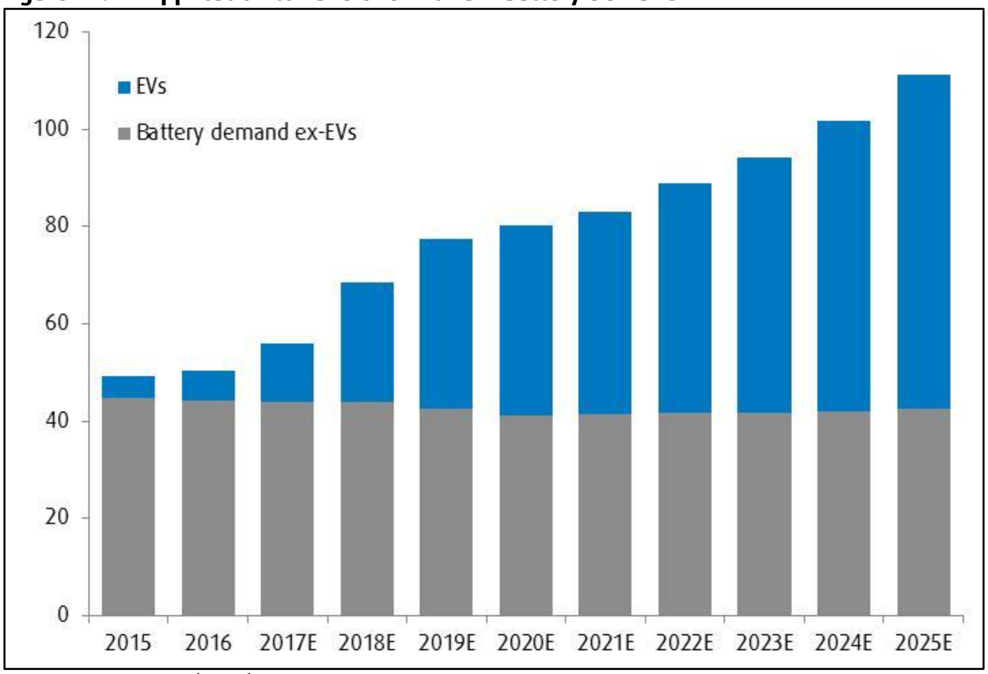
Figure 16: Specifications of Rechargeable Batteries

	Lead Acid	Nickel Cadmium	Nickel Metal Hydride	Sodium Nickel Chloride	Lithium Ion
Descriptor	PbA	NiCd	NiMh	NaNiCl	Li-ion
Specific Energy (Wh/kg)	30-40	45-80	60-120	100-120	**140-190**
Specific Power (W/kg)	150-250	150-200	250-1000	150	**600-3000**
Nominal Voltage (V)	2.0	1.2	1.2	2.6	**3.2-3.8**
Life Cycles	300-800	1000-2000	500-1500	~1000	**> 1000**
Self-Discharge Rate	3-5%	20%	30%	-	10%

Definitions:	
Specific Energy	Measures capacity or the amount of energy that the battery can store (Wh) in relation to its weight (kg). This measure is analogous to the size of the gas tank and the mileage the car can get between fill-ups.
Specific Power	Relates the battery's power (W) per weight (kg) or horsepower.
Nominal Voltage	Indicates the number of cells needed in the battery pack. The higher the voltage (V), the lower the number of cells needed in the pack.
Life Cycles	The number of times that the battery can be charged and discharged before it reaches its end-of-life.
Self-Discharge Rate	Internal chemical reactions when not in use that reduces the amount of energy stored.

Source: Warner, 2015; Liu *et al.,* 2017

Figure 17: EV Application to Take Over Lithium Battery Demand



Source: BMO Capital Markets

Despite all the advantages, lithium ion batteries do suffer from a number of technological impediments that are inhibiting widespread adoption of BEVs particularly in hot or cold climates. **These technological hurdles contribute a great deal to battery costs and endanger mass market consumption.**

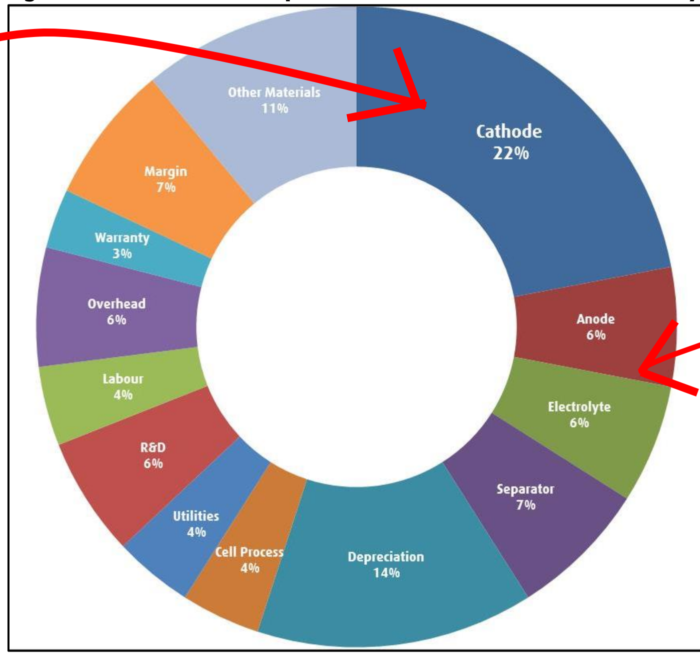
5. Battery Costs Are Declining

Battery costs expected to decline to $100-125kWh by the next decade

Many companies are looking to source cheaper raw materials (i.e. cobalt), improve the life cycle of the battery and increase economies of scale in order to improve costs. **Based on our models and industry sources, we expect battery costs to decline from ~$200kWh to $100-125/kWh by the next decade**. We believe that decreasing costs will be necessary to offset the eventual government incentive phase outs to ensure EV cost parity continues to progress forward and achieving a battery cost of ~$100/kWh would lower the sticker price of an EV by a few thousand dollars, which accounts for a large portion of the subsidies paid by governments. Since it is likely that these subsidies will be phased out as the EV market begins to scale up, reducing the cost of this input is essential to maintain the momentum. The battery represents a third of the cost of a BEV with the cathode (raw materials, manufacturing, coatings, etc.) representing about 22% of the cost.

Figure 18: The Cathode Represents 22% of the Estimated Battery Costs

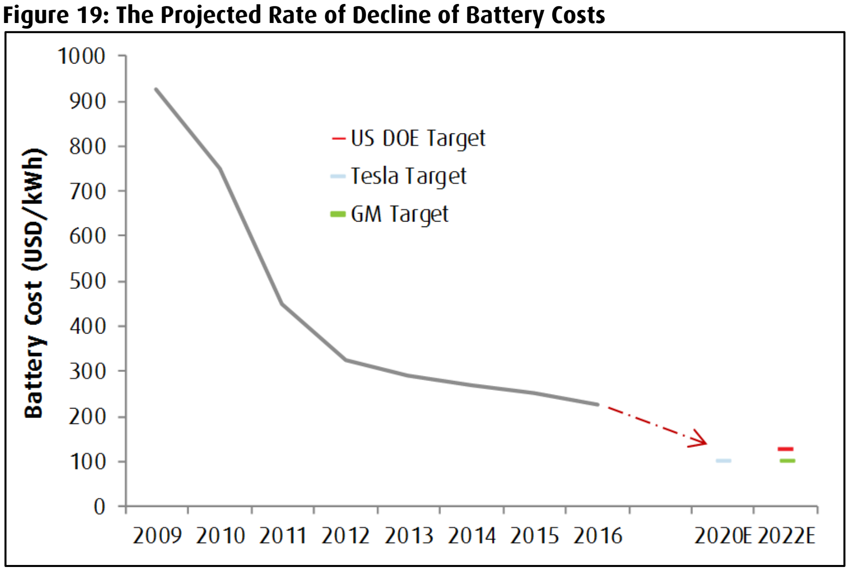
Cathode=22% of battery costs and includes raw materials, manufacturing, coatings



Anode, electrolyte and separator make up another 19% of the cost

Source: U.S. DOE

Figure 19: The Projected Rate of Decline of Battery Costs



Source: Company Reports, BMO Capital Markets

Battery Costs to Decline at an Increasing Rate — The Gigafactory Effect

Value of innovation in decreasing battery costs has been greatly underestimated

We also expect lithium-ion battery costs to decline at an increasing rate versus the last five years as global battery producers build and expand large-scale "gigafactories," and unlock added cost savings from economies of scale. In addition to this, we see the trend of battery manufacturers vertically integrating upstream battery material production (cathode, anode, etc.) internally to reduce production costs. Tesla, through its partnership with Panasonic, has a battery cost target of $100/kWh by 2020 and has its Nevada based Gigafactory 1 already producing batteries for its Powerwall as well as the Model 3. The company also has a goal of increasing production capacity to 35GWh by the end of 2018 and 52GWh by 2025 from the ~4GWh capacity currently available.

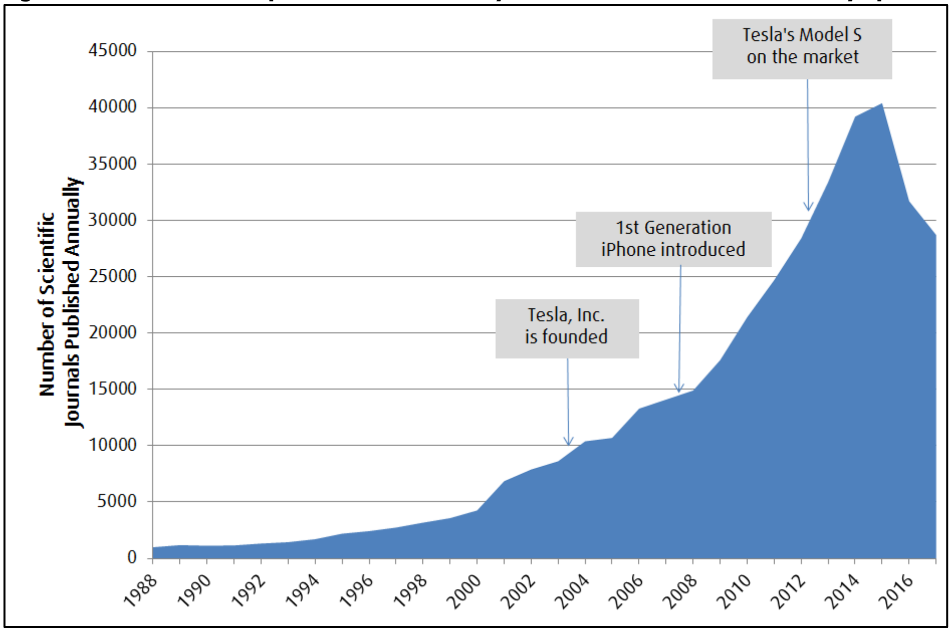
This scale up trend has been increasingly rapid in the industry over the last year:

- May 2017 → *Daimler AG* announced that it had begun construction of a $562 million lithium battery factory in Germany with the intentions of bringing 10 new EV models to the market by 2020. Thailand's *Energy Absolute Public Company Limited* announced plans for a $2.9 billion factory in Asia with the hopes of scaling to 50GWh a year by 2020.
- September 2017 → The Swiss engineering firm *ABB* announced that it would team up with Stockholm-based *Northvolt AB* to build Europe's largest lithium ion battery factory and has already invested $11.8 million for the initial phase of the project.
- October 2017 → *LG Chem Ltd.* announced plans to open a $1.63 billion lithium-ion battery factory in Wroclaw, Poland in order to keep up with EV demand in Europe. The consortium, consisting of *Magnis Resources Ltd*, *Charge CCCV LLC*, *Boston Energy and Innovation*, *C&D Assembly* and *Primet Precision Materials,* announced plans to invest in a $130 million gigafactory in upstate New York.
- November 2017 → *BMW* announced a $240 million investment in a new battery centre to increase the range of its EVs to 430 miles (690km) by 2021. The new facility is expected to be completed in 2019.

Increased Intellectual Capital and Investment

The scientific and industry efforts to reduce costs via technological improvement have also grown dramatically over the last decade. In the 1990s, there were about a thousand peer-reviewed articles about lithium ion batteries published annually. There are now about 30,000 published annually with a dramatic ramp-up in the years following the introduction of the iPhone and Tesla's Model S. While one could argue that there has been a significant increase in publications in general because of the introduction of improved technologies in the laboratory setting, this growth signifies the substantial intellectual investment in this space. Furthermore, researchers at UC Berkeley used a two-factor model to show that **the value of innovation has been greatly underestimated in cost models and that because of the explosion of R&D and patent investment, cost reductions are likely to become more rapid and be achieved in a much shorter timeframe** than previously expected.

Figure 20: Intellectual Capital Has Been Greatly Increased in the Lithium Battery Space



Source: BMO Capital Markets

6. The Tesla Effect – Making EVs a 'Must Have' Item

Tesla has championed the comeback of the electric car. When the Toyota Prius was introduced, car enthusiasts may have admired the battery technology or fuel economy, but no one would have called it "cool." Tesla's attractive and sleek BEV designs and driving experience have compelled governments, car companies and consumers alike to rethink the electric car. Tesla is clearly the 'disruptor' in the automotive space and forced established OEMs such as BMW, Mercedes and GM to take EVs seriously. Tesla topped Consumer Reports' Annual Owner Satisfaction Survey for the second year in a row with a rating of 90, again beating out long-time favourites such as Porsche (85) and Audi (76). Tesla's successful rollout of the model S P100D, with its record breaking acceleration on Ludicrous Mode, has even compelled high-end luxury car manufacturer Aston Martin to develop its own EV announcing that its RapidE is expected to have a limited run as early as 2019. Tesla has clearly changed the game on all fronts.

Figure 21: Tesla's Sleek Design Has Changed the Way People Think About EVs

Source: Toyota Motor Car and Tesla, Inc.

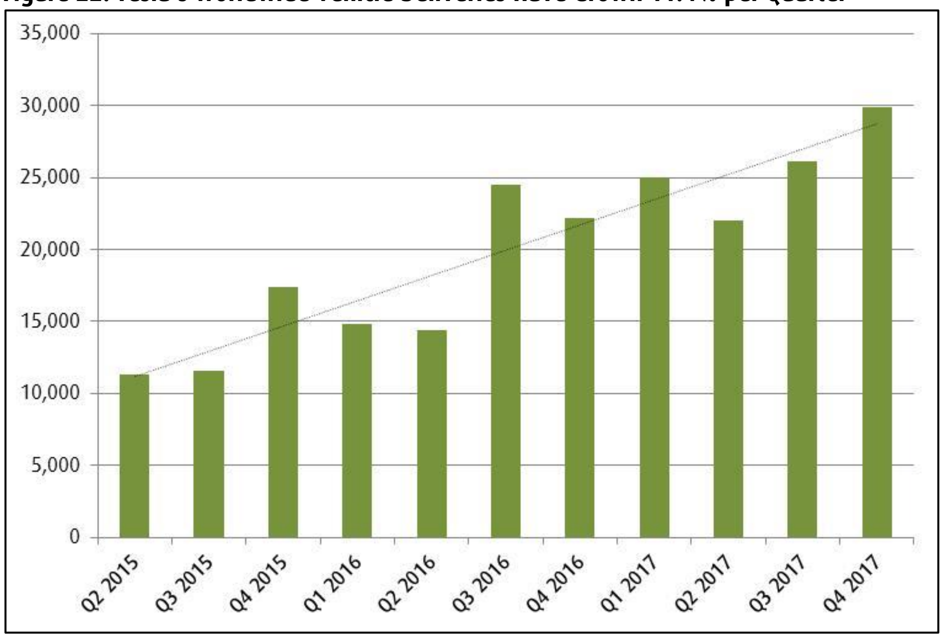
The Model S Was the Game Changer

The Model S has become one of the most popular luxury cars on the market today and the more affordable Model 3 reportedly has ~400,000 pre-orders to date. While the highly-publicized production failures have slowed delivery, Tesla announced in November 2017 that deliveries should accelerate by the end of March and its full-scale rollout will now be late 2018. While there have been some cancellations due to the delays, many customers remain loyal to the brand. Typical Model S drivers bought the very high-priced car in the early days for many reasons other than the environment and there is certainly an aspirational buzz among consumers. However, we don't see Tesla as being a long-term leader in terms of global sales necessarily, but the company has 'set the bar' on performance, smoothness and design (i.e., in-car panel) to a level that is pressuring other OEMs to compete.

Tesla has delivered 219,000 vehicles since early 2015 and...

...~400,000 pre-orders of the affordable Model 3

Figure 22: Tesla's Worldwide Vehicle Deliveries Have Grown 11.4% per Quarter



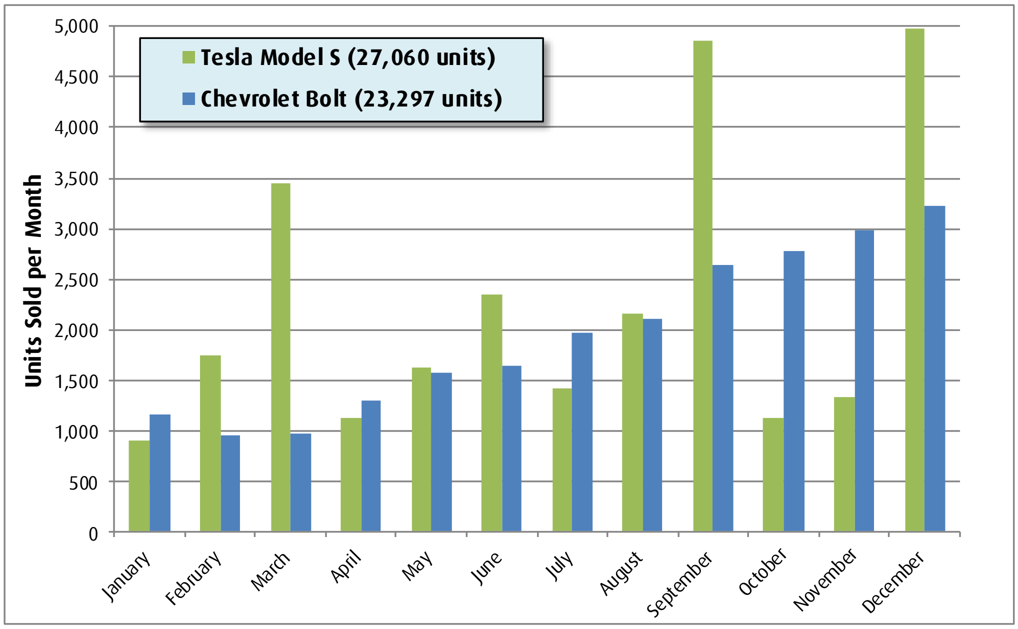
Source: Statista

But Chevy Bolt Is Not Far Behind – At Least in Units Sold

Even traditional OEMs such as GM are getting into the game. GM announced in October 2017 that it would aggressively pursue an all-electric, zero emissions future with two new BEVs in 2018, and 18 more by 2023. An announcement such as this would have indeed raised our eyebrows if it were not for Chevy's very successful launch of the Bolt (introduced in December 2016), which garnered 21.8% of the U.S. market in its first year on the market. GM also plans to leverage its position in China (last year it sold 3.6 million in China compared to 3 million in the U.S.) to launch 10 EV models there by 2020. While there have been many announcements such as these, GM has our attention, for now.

GM has aggressively pursued electrification and has announced two BEVs to be introduced in 2018

Figure 23: Tesla Model S vs. Chevy Bolt (Units Sold in the U.S. in 2017)



Source: carsalesdatabase, BMO Capital Markets

Still, Tesla is the one to beat even among Chinese OEMs. In December 2017, the private Shanghai-based electric car start-up called NIO (established in 2014 as NextEV Inc.) announced that it has launched its first mass-produced EV model, stating that the ES8 would be a cheaper SUV than Tesla's Model X (MSRP US $67,765 vs. US$126,470 in China). Some industry watchers have stated that the ES8 could be serious competition and one worth watching. In addition, Porsche just announced that it has doubled its EV commitment to $7.5 billion and will be launching its Mission E line of cars (a direct competitor to the Model S) by 2020.

Figure 24: The Similarities of the Chevy Bolt and the NIO ES8 to Tesla models

	Chevy Bolt	Tesla Model 3	Tesla Model S 75D	NIO ES8	Tesla Model X
Base MSRP (U.S)	US$35,478	~US$35,000	US$75,700	US$67,765 (China)	US$80,700
Battery Size	60kWh	60kWh	75kWh	70 kWh	75kWh
Horsepower	200hp	302hp	259hp	550hp	259hp
Battery Range	383km	300km	417km	355km	381km
	238miles	186miles	259miles	220miles	236miles
Cooling	Liquid	—	liquid	liquid	Liquid
Weight	1,625kg	1,610kg	2,108kg	2,460kg	2,350kg
	3580lb	3,549lb	4,647lb	5,423lb	5,181lb
0-100 km/h (62mph)	6.5 seconds	5.6 seconds	5.4 seconds	4.4 seconds	6.2 seconds
Motor	150kW	228kW	193kW	240kW	193kW
Top Speed	146km/h	209km/h	225 km/h	180 km/h	210 km/h
	91mph	130mph	155mph	112mph	130mph
Drivetrain	FWD	RWD	AWD	AWD	AWD
	AWD (exp. 2019)	AWD (exp. 2018)			

Source: Industry & Company Reports, BMO Capital Markets

7. EV Cost of Ownership Nearing ICE Today

Longer payback times have been a key hurdle to mass market penetration

One of the key hurdles to achieving mass market penetration has been the longer payback times of the initial EV purchase price as well as the uncertain ongoing costs (e.g. charging costs, battery replacement, etc.). Early adopters tended to be environmentally conscious with higher income brackets that could buffer any costly surprises. For the average car buyer, the potential fuel savings of an EV did not justify its premium price over ICE vehicles. **Although affordability has been improving (declining battery costs and subsidies), we believe that EV-ICE cost parity is already fairly close based on the cost of ownership over a vehicle's typical lifespan (we assume 15 years), even excluding subsidies.** In addition, EVs typically have lower maintenance costs, which help to reduce the total cost of BEV ownership.

Figure 25: We See the Cost Parity Already Narrowing on Some Models

Current EV-ICE Cost of Ownership Comparison		
Vehicle Model	2017 Volkswagen e-Golf	2017 Volkswagen Golf
Purchase Price	$30,495	$20,995
U.S. Purchase Subsidy	($7,500)	
Annual Fuel/Electricity Cost[1]	$598	$955
Annual Operating Cost[2]	$2,702	$3,213
One-Time Battery Replacement Cost[3/]	$7,160	
Total Cost of 15 year Ownership	**$79,655**	**$83,515**

Current PHEV-ICE Cost of Ownership Comparison		
Vehicle Model	2017 Kia Optima Plug-in	2017 Kia Optima
Purchase Price	$35,210	$22,200
U.S. Purchase Subsidy	($4,919)	
Annual Fuel/Electricity Cost[1]	$676	$1,082
Annual Operating Cost[2]	$2,933	$3,340
One-Time Battery Replacement Cost[3/]	$1,960	
Total Cost of 15 year Ownership	**$86,386**	**$88,530**

Note: Assumes 12,000 miles driven per year and 55% city driving.
1. Electricity cost of $0.17/kWh and gasoline costs of $2.38/gal (California)
2. Operating costs include insurance, maintenance, tire replacement, taxes, etc.
3. Since all OEMs include an 8-year battery warranty, we are using a cost of $200/kWh
4. VW e-Golf battery pack size is 36kWh and the Kia Optima PHEV is 10kWh

Source: US DOE, Company Reports, BMO Capital Market

8. Reducing Range Anxiety

Lengthier charging times and extra road side assistance costs create more anxiety for drivers

Range anxiety is often cited as a major impediment to wider market penetration. The thought of getting stranded on the daily commute because of your BEV rather than for reasons beyond your control (road blocks, traffic etc.) is off-putting to say the least. While many believe that it should not be a concern in the first place, the thought of lengthy charge times and added road side assistance costs do create more anxiety for drivers than the thought of running out of gas. Currently, to use a BEV for long-haul travel, drivers would need to map out charging stations, check what level they are at, and plan accordingly. Range capabilities per charge can also vary based on the average driving speed and outside temperature (i.e., the range for the Tesla Model S is closer to 530 miles if driven at an average speed of 45 mph). We do believe that there has been a big effort to reduce range anxiety in the last two years. For example, Tesla increased the range of its roadside assistance program from 50 miles to 500 miles in order to put drivers more at ease and the American Automobile Association (AAA) has introduced charging trucks in an effort to reduce the costs of roadside assistance.

We address this issue in more depth later in this report, but for now, we believe that range anxiety should lessen over time as the battery technology improves. The average BEV model has a range of

100-150 miles per charge and top-end models such as Tesla carry larger battery packs that increase ranges to 250-350 miles (400-560km) per charge. The Chevrolet Bolt is the first affordable BEV to reach 238 miles (383km), and as a result, was named 2017 Motor Trend Car of the Year. Furthermore, Figure 26 shows that most models can now be fast charged in 25-60 minutes. Therefore, we believe that this trend of increasing vehicle range between charges, along with increasing fast-charging infrastructure, will alleviate range anxiety and bring more consumers to the table.

Figure 26: Combatting Range Anxiety Charge and the Cost Parity Issue (Estimated Annual Cost and Emissions Savings)

		Range		Time to Charge from Empty (hours)			Fast Charge	Annual Cost (C$) per 20,000km		Annual Premium for	Annual Emissions CO_2 (kg) per 20,000km		Emissions
Manufacturer	Model	(miles)	(km)	L1	L2	L3 (to 80%)	Type[1]	EV	Gas Car	Gas Car (%)	EV	Gas Car	Premium (%)
BMW	i3	114	183	21	5	30 min.	SAE CCS	402	1,910	**375.1%**	1,102	4,480	**306.5%**
Smart	Forttwo ED	58	93	–	3	–	–	438	1,910	**336.1%**	1,140	4,484	**293.3%**
Chevrolet	Bolt	238	383	26	9.5	1 hour	SAE CCS	400	1,900	**375.0%**	1,090	4,400	**303.7%**
Ford	Focus EV	115	185	23	5.5	30 min.	SAE CCS	440	1,870	**325.0%**	1,220	4,400	**260.7%**
Hyundai	Ioniq Electric	124	200	19	4.5	35min.	SAE CCS	960	4,850	**405.2%**	970	4,855	**400.5%**
Kia	Soul Electric	93	150	19	4	25min.	CHAdeMO	440	1,870	**325.0%**	1,130	4,400	**289.4%**
Nissan	Leaf	107	172	21	6	30min.	CHAdeMO	400	2,070	**417.5%**	790	4,860	**515.2%**
Tesla	Model S	249	400	42	10	1 hour	SP	450	2,490	**453.3%**	1,150	4,880	**324.3%**
Tesla	Model X	237	381	52	12	1 hour	SP	500	2,460	**392.0%**	1,278	5,780	**352.3%**
Volkswagen	e-Golf	125	201	25	5.3	45min.	SAE CCS	390	1,870	**379.5%**	989	4,400	**344.9%**
	Average	146	235	28	6	40min	-	482	2,320	**378.4%**	1,086	4,694	**339.1%**

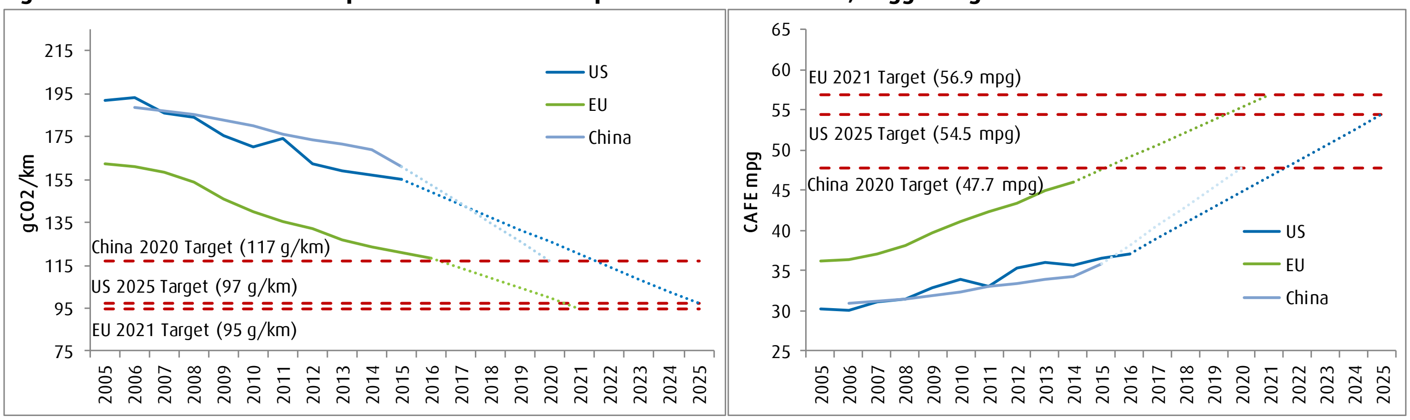
		Electirc Range		Gas Range		Time to Charge from Empty (hours)		Annual Charge Cost (C$)		Annual Cost Premium for	Annual Emissions (kg)		Emissions
Plug-In Hybrids		(miles)	(km)	(miles)	(km)	L1	L2	PHEV	Gas Car	a Gas Car (%)	PHEV	Gas Car	Premium (%)
Audi	A3 Sportback e-tron	16	26	360	579	6	2.5	1,210	1,870	**54.5%**	2,790	4,400	**57.7%**
BMW	i3Rex	97	156	80	129	23	5	630	2,000	**217.5%**	1,490	4,480	**200.7%**
BMW	i8	15	24	316	509	6	2	1,470	2,080	**41.5%**	3,370	4,880	**44.8%**
BMW	330e	14	23	346	557	6	2	1,400	2,100	**50.0%**	3,230	3,560	**10.2%**
BMW	530e	15	24	360	579	6	3	1,580	2,080	**31.6%**	3,620	4,880	**34.8%**
BMW	740Le xDrive	14	23	326	525	6	3	1,610	2,180	**35.4%**	3,270	4,880	**49.2%**
BMW	X5 xDrive 40e	14	23	526	846	6	3	1,580	2,080	**31.6%**	3,620	4,880	**34.8%**
Cadillac	CT6 PHEV	31	50	440	708	13	4.5	1,370	2,170	**58.4%**	3,200	4,860	**51.9%**
Chevrolet	Volt	53	85	367	590	13	4.5	530	1,870	**252.8%**	1,390	4,400	**216.5%**
Chrysler	Pacifica PHEV	33	53	533	858	11	2.5	990	2,500	**152.5%**	2,390	5,770	**141.4%**
Ford	Fusion Energi	22	35	502	808	5	2.5	920	2,070	**125.0%**	2,150	4,850	**125.6%**
Honda	Clarity PHEV	42	67	329	530	–	2.5	570	2,070	**263.2%**	1,460	4,850	**232.2%**
Hyundai	Sonata PHEV	27	43	560	901	7	3	950	2,170	**128.4%**	2,150	4,860	**126.0%**
Karma	Revero	32	51	188	303	15	4	1,790	2,180	**21.8%**	3,700	4,880	**31.9%**
Kia	Optima PHEV	29	47	581	935	7	3	890	2,170	**143.8%**	2,010	4,860	**141.8%**
Mercedes	GLE 550e	12	19	447	719	6	2	2,160	2,580	**19.4%**	4,800	5,780	**20.4%**
Mercedes	S550e	14	23	436	702	6.5	3	1,680	2,180	**29.8%**	3,840	4,880	**27.1%**
Mini	SE Coutryman S E ALL4	12	19	258	415	–	2.5	1,830	2,230	**21.9%**	3,490	4,880	**39.8%**
Mitsubishi	Outlander PHEV	32	52	320	515	–	3.5	1,460	2,460	**68.5%**	3,380	5,770	**70.7%**
Porsche	Cayenne S E Hybrid	14	23	477	768	7.5	3	1,960	2,580	**31.6%**	4,350	5,780	**32.9%**
Porsche	Panamera S E Hybrid	16	25	544	875	6.5	2	1,470	2,180	**48.3%**	3,260	4,880	**49.7%**
Toyota	Prius Prime	25	40	618	995	6	2	670	2,170	**223.9%**	1,570	4,860	**209.6%**
Volvo	S90 T8 eAWD	21	34	407	655	–	3	1,320	2,070	**56.8%**	1,320	2,070	**56.8%**
Volvo	XC60 T8 eAWD	13	21	329	529	6.5	2.5	1,550	2,460	**58.7%**	3,580	5,770	**61.2%**
Volvo	XC90 T8 eAWD	19	30	329	529	6.5	2.5	1,570	2,580	**64.3%**	3,510	5,780	**64.7%**
	Average	25	41	399	642	8	3	1,326	2,203	**89.3%**	2,918	4,870	**85.3%**

Source: plugndrive.ca

Battleground #1 → OEMs Race to Get BEV/PHEV on the Road

The various standards set by governments have serious implications for the auto market as they target vehicle carbon dioxide emission levels (gCO_2/km) and fuel efficiency (mpg). While there have been environmental targets in the past, **the latest policies we have seen will require unprecedented responses from OEMs to be compliant**. For one, ICE emission capabilities will have to be drastically improved (increasing the cost per ICE vehicle) and/or ensure EVs account for a significant portion of the portfolio mix to avoid financial penalties from non-compliance. Thus this first battleground, BEV and PHEV OEMs have some pretty clear lines.

Figure 27: Vehicle Standards Require Faster Rates of Improvement Than Before, Suggesting More Is Needed From OEMs



Note: Vehicle standards are based on lab testing, real world mpg results (as advertised by OEMs) are ~80% of lab tests.

Source: EPA, NHTSA, EC, ICCT

Fuel Efficiency Standards Would Have to Double to Meet Emissions Standards

ICE fuel efficiency would have to double to meet environmental standards if EV penetration does not increase

We estimate that ICE fuel efficiency improvement rates would have to *effectively double* in order to meet environmental standards without help from much greater EV adoption. We do not see this as a possibility and see increasing EV penetration as inevitable. In our models, global EV penetration would need to reach ~12% in order to comply with environmental regulatory targets by 2025.

With these pressures, along with stronger demand from the consumer side to reduce local emissions, car manufacturers have been aggressively pursuing strategies to put their mark on the EV road map. Tesla has indeed fired up the competitive juices and it seems like there are daily announcements in this space. OEMs need access to battery technology and as such have partnered with leading companies in this space. It is clear to us that OEMs are feeling the pressures from government regulations and various proclamations, and are afraid of losing market share. Anyone visiting recent global auto shows (e.g., Frankfurt, Beijing, Detroit) would have seen the electrification focus. There is also pressure to set bold targets politically and competitively. Based on the industry targets we have seen so far, EV penetration is expected to be ~14.3% in 2025 and not the 10% we are predicting.

- The Hyundai Motor Group and the Kia Motor Corporation expect to produce more than 100,000 electric cars next year. These include Hyundai's Kona EV (18,600 units) and IONIQ Electric (48,000) and Kia's Niro EV (21,000) and Soul EV (~12,400). The two brands plan to launch eight new BEVs over the next couple of years and Hyundai announced that a 500km (311 miles) range model is expected to be launched in 2021.

- Volkswagen (perhaps spurred by the 2015 diesel-gate scandal) recently increased its target to 3M annual EV sales by 2025 (~1.5M in China) with 80 new EV models (50 BEV, 30 plug-in) by the same year, and also expects to offer an electric version of its 300 VW line by 2030.

- Tesla, Inc. expects to sell 0.5M and 1.0M EVs in 2018 and 2020, respectively, versus its 2017 sales run rate of ~100,000 cars. We expect the Model 3 headaches will be remedied soon and that the model will be significantly contributing to sales by 2019. Tesla is also expected to unveil an electric crossover, currently referred to as Model Y, sometime in 2018.

- Daimler AG and the BMW Group have both set goals of 15-25% of total company sales to be EVs by 2025. Daimler has pushed its Mercedes-Benz subsidiary into spending US$1 billion to refurbish a 20-year old factory in Alabama to produce electrified versions of its SUVs. BMW plans to mass produce a BEV by 2025 and offer 12 new EV models by 2025.

- Renault-Nissan-Mitsubishi Alliance expects 1.5 million cumulative sales by 2020. The Alliance 2022 fund was set up in 1999 to promote access to entrepreneurial ideas. It also announced at the beginning of 2018 that the fund plans to spend over $1billion on start-ups over the next five years.

- Back in 2015, Ford Motor Co. announced that it would invest $4.5 billion in its in-house electric car program. Now, the company will be increasing its spending to S11 billion and expects to have 40 new EV models (BEV and PHEV) by 2022, which will include an all-electric 300 mile SUV, hybrid versions of the F-150 pick-up truck, the Mustang, and an electric van. In November 2017, a $756 million joint venture between Ford and Chinese automaker Zotye was announced that would see the introduction of a new EV brand in that market. Ford will also be introducing 15 EV models under the Ford and Lincoln brands to the Chinese market by 2025.

- Honda aims to have EVs represent two-thirds of global car sales by 2030, and by 2025 in Europe. In November 2017, Honda announced that every new model it produces for Europe will have an electrified version.

- Volvo (owned by China's Zhejiang Geely Holding Group) announced that starting in 2019, every new model developed by the company will be BEV, PHEV or HEV expecting to reach cumulative EV sales of 1 million units by 2025.

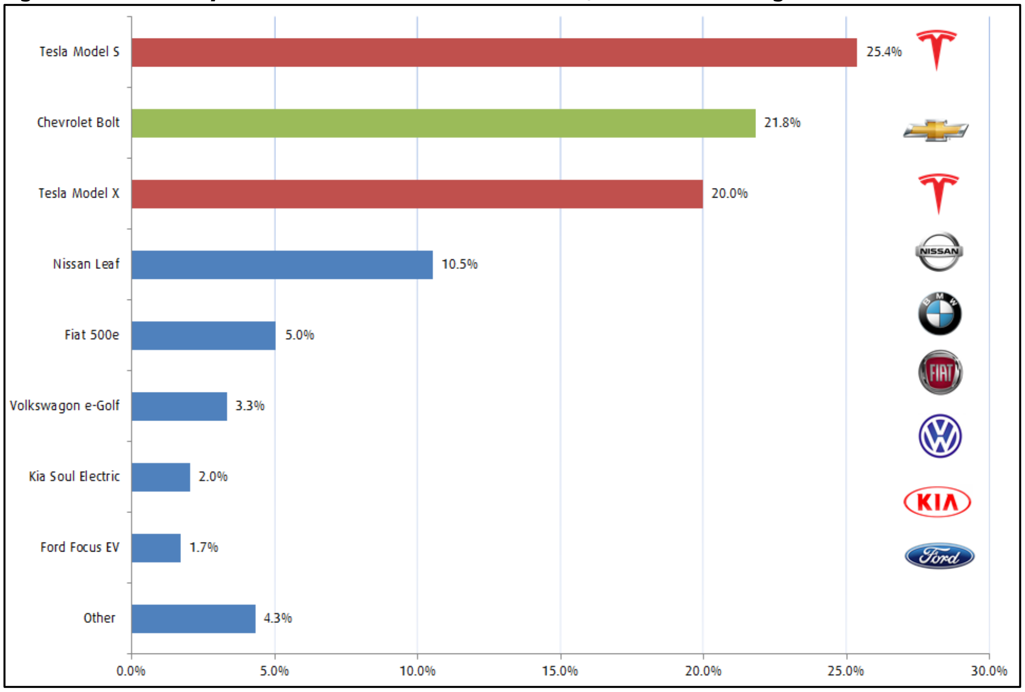
- GM expects to release two new BEV models in 2018 and 18 more by 2023. It already has had a very successful rollout of its Chevrolet Bolt model, garnering 21.8% of the North American market in its first year on the market. We also believe that the Bolt is the most likely model for fleet operators in North America to begin making this shift. Furthermore, industry reports suggest that GM will also be introducing PHEV versions of its popular large SUVs and pickup trucks.

Tesla and Chevy Rule the North American Market

The BEV market in the U.S. market is currently dominated by Tesla and GM. The Chevrolet brand made a big impact when it introduced its Bolt in December 2016. Together, Tesla and Chevy now represent 67.2% of the market. The Nissan Leaf has 10.5% of the market and the last 22.3% of the market is shared by BMW, Fiat and a handful of other OEMs.

Tesla and Chevy now represent 67.2% of the U.S. BEV market

Figure 28: Tesla May Still Dominate the U.S BEV Market, But GM Is Closing In



Source: BMO Capital Markets

GM may be setting the stage to become a serious contender in the EV space

An old school automotive company such as GM is probably the last company one would have expected to grab 21.8% of the BEV market share on its first try. However, there is good reason for its fast track to significant market share. Over the last decade, one of GM's V-8 testing facilities was transformed into the largest automotive battery lab in North America. It even has specialized climatic testing chambers that simulate arctic temperatures as low as -85°F (-65°C) to Arizona's desert-like conditions during a heat wave 185°F (85°C). There is no denying that GM's intention from the get-go was to make an impact – and fast – rather than merely to offer a model that would give it a toe-hold in this market. It will be interesting to see how the expected 2018 rollout of Tesla's Model 3 will impact Bolt sales.

While Nissan has been slowly losing market share (24.7% in 2015, 17.0% in 2016 and 10.5% in 2015), we know that many Nissan Leaf customers are waiting for the new, much-anticipated 2018 model, which is expected to be released shortly. The Nissan Leaf has long been a sentimental favourite, but issues with range and temperature have made uptake much slower than Tesla's models. It did celebrate the delivery of its 300,000th car and its strong brand following may help it to regain some of the market share it once enjoyed. But while we will monitor the rollout of the new Leaf model, we believe **Tesla and Chevrolet are really the ones to watch**.

Figure 29: Of the Current EVs on the Market in North America, Tesla and GM Are the Ones to Watch

Battery Electric Cars (BEVs)		Pack Size			Range		U.S. Sales (000s)			BEV Market	Base Price	Consumer	Cost of ICE	BEV	BEV Premium
Brand	**Model**	**(kWh)**	**MPGe[1]**	**hp**	**(miles)**	**(km)**	**2015**	**2016**	**2017**	**Share (US)**	**(USD)[2]**	**Cost (USD)[3]**	**(USD)[4]**	**Premium**	**(with subsidy)**
BMW	i3[5]	33	120	170	114	183	11,024	7,625	6,276	5.9%	45,445	37,945	—	—	—
Mercedes-Benz	B250e (B-Class)[6]	32	84	177	100	161	1,906	632	744	0.7%	40,895	33,395	35,900	13.9%	-7.0%
Chevrolet	**Bolt[7]**	**60**	**119**	**200**	**238**	**383**	**—**	**579**	**23,297**	**21.8%**	**37,495**	**29,995**	**24,575**	**52.6%**	**22.1%**
Fiat Chrystler	500e	24	112	111	84	135	6,194	5,330	5,380	5.0%	33,990	26,490	20,990	61.9%	26.2%
Ford	Focus EV	34	107	143	115	185	1,582	901	1,817	1.7%	29,995	22,495	18,735	60.1%	20.1%
Honda	Clarity Electric[8]	26	114	161	89	143	—	—	1,121	1.1%	199/mth	—	—	—	—
Hyundai	Ioniq Electric[9]	28	136	105	124	200	—	—	432	0.4%	30,335	22,835	—	—	—
Kia	Soul Electric	27	105	109	111	179	1,015	1,728	2,157	2.0%	33,145	25,645	18,595	78.2%	37.9%
Mitsubishi	i-MieV[10]	16	112	66	62	100	115	94	6	0.0%	23,845	23,845	—	—	—
Nissan	Leaf[11]	40	112	147	150	241	17,269	14,006	11,230	10.5%	30,875	23,375	21,225	45.5%	10.1%
Smart	Fortwo ED	18	108	—	58	93	1,387	657	544	0.5%	24,550	17,050	15,400	59.4%	10.7%
Tesla	**Model S**	**90**	**100**	**532**	**290**	**467**	**25,202**	**28,896**	**27,060**	**25.4%**	**69,200**	**61,700**	**—**	**—**	**—**
Tesla	**Model X**	**90**	**90**	**532**	**285**	**459**	**—**	**18,223**	**21,315**	**20.0%**	**80,700**	**73,200**	**—**	**—**	**—**
Tesla	**Model 3[12]**	**65**	**—**	**271**	**219**	**352**	**—**	**—**	**1,772**	**1.7%**	**36,000**	**28,500**	**—**	**—**	**—**
Volkswagen	e-Golf	36	119	134	125	201	4,232	3,937	3,534	3.3%	30,495	22,995	20,715	47.2%	11.0%
	Average	41	110	204	144	232	6,993	6,884	7,112	—	39,069	32,105	22,017	52.4%	16.4%
						Total	69,926	82,608	106,685						
						CAGR	—	18.1%	29.1%						

Plug-In Hybrids (PHEV)[13]		Pack Size			Electirc Range		Gas Range		U.S. Sales			Base Price	Est. Tax	Consumer	Cost of ICE	PHEV	PHEV Premium
Brand	**Model**	**(kWh)**	**MPGe[1]**	**hp**	**(miles)**	**(km)**	**(miles)**	**(km)**	**2015**	**2016**	**2017**	**(USD)[2]**	**Credit (USD)**	**Cost (USD)[3]**	**(USD)[4]**	**Premium**	**(with subsidy)**
Audi	A3 Sportback e-tron	9	34	204	16	26	360	579	—	4,280	2,877	40,475	4,500	35,975	32,925	22.9%	9.3%
BMW	i3Rex[14]	33	79	170	97	156	80	129	—	—	—	49,295	7,500	41,795	—	—	—
BMW	i8	7	28	357	15	24	316	509	2,265	1,594	488	144,395	5,000	139,395	—	—	—
BMW	330e	8	30	180	14	23	346	557	—	870	4,141	44,695	4,000	40,695	39,745	12.5%	2.4%
BMW	530e	9	70	180	15	24	360	579	—	—	3,772	52,395	4,700	47,695	52,195	0.4%	-8.6%
BMW	740e xDrive	9	27	255	14	23	326	525	—	23	707	90,095	4,700	85,395	84,500	6.6%	1.1%
BMW	X5 xDrive 40e	9	24	240	14	23	526	846	892	5,995	3,259	63,200	4,600	58,600	58,900	7.3%	-0.5%
Cadillac	CT6 PHEV	18	26	335	31	50	440	708	—	—	207	76,090	7,500	68,590	55,090	38.1%	24.5%
Chevrolet	Volt	18	42	149	53	85	367	590	15,393	24,739	20,349	34,095	7,500	26,595	24,575	38.7%	8.2%
Chrysler	Pacifica PHEV	16	32	260	33	53	533	858	—	—	4,597	47,885	7,500	40,385	30,090	59.1%	34.2%
Ford	C-Max Energi	8	39	188	21	33	549	884	7,591	7,957	8,140	27,995	4,000	23,995	24,995	12.0%	-4.0%
Ford	Fusion Energi	8	42	188	22	35	502	808	9,750	15,938	9,632	33,995	4,000	29,995	22,995	47.8%	30.4%
Honda	Clarity PHEV[9]	17	110	181	42	67	329	530	—	—	903	34,290	7,500	26,790	—	—	—
Hyundai	Sonata PHEV	10	39	67	27	43	560	901	160	3,095	2,535	35,435	2,500	32,935	22,935	54.5%	43.6%
Karma	Revero	21	54	235	32	51	188	303	—	—	—	130,000	—	—	—	—	—
Kia	Optima PHEV	10	40	67	29	47	581	935	—	—	1,512	35,000	4,900	30,100	23,395	49.6%	28.7%
Mercedes	C350e	6	30	275	20	32	—	—	—	171	817	43,000	4,000	39,000	39,850	7.9%	-2.1%
Mercedes	GLE 550e	9	21	116	12	19	447	719	—	231	463	67,000	4,100	62,900	52,997	26.4%	18.7%
Mercedes	S550e	9	26	436	14	23	436	702	118	550	666	95,325	4,700	90,625	90,895	4.9%	-0.3%
Mini	SE Coutryman[15]	8	—	221	25	40	—	—	—	—	475	37,650	4,000	33,650	26,950	39.7%	24.9%
Mitsubishi	Outlander PHEV[16]	12	—	197	—	—	—	—	—	—	99	35,500	—	—	—	—	—
Porsche	Cayenne S E Hybrid	11	22	416	14	23	477	768	1,103	2,111	1,574	79,750	5,300	74,450	61,650	29.4%	20.8%
Porsche	Panamera S E Hybrid	9	—	416	16	25	544	875	407	393	18	99,975	5,000	94,975	86,050	16.2%	10.4%
Toyota	**Prius Prime**	**9**	**54**	**121**	**25**	**40**	**618**	**995**		**2,422**	**15,056**	**27,995**	**4,500**	**23,495**	**—**	**—**	**—**
Volvo[17]	XC60 t8 eAWD	10	—	400	13	21	329	529	—	—	531	53,895	5,000	48,895	42,495	26.8%	15.1%
Volvo	S90 T8 PHEV	9	25	400	19	30	329	529	—	—	117	69,095	4,600	64,495	47,895	44.3%	34.7%
	Average	12	41	241	25	41	415	668	4,187	4,691	3,456	59,558	5,067	52,559	46,056	27%	15%
								Total	37,679	70,369	82,935						
								CAGR	—	86.8%	17.9%						

1. MPGe means 'miles per gallon equivalent' and is a figure that the EPA converts the power use of an electric car into MPG.
2. MRSP from caranddriver.com, retrieved December 30th, 2017.
3. Estimated tax credit for all BEVs is US$7,500. Some states may provide different incentives.
4. Cost of an ICE car includes direct comparisons (e.g. Kia Soul EV to its ICE equivalent) or we made a close comparison.
5. On December 3, 2017, BMW issued a massive recall of its i3 model sold in the U.S. between 2014-2018 that wiil affect about 300 thousand vehicles for a seatbelt issue that does not meet NHTSA requirements.
6. Mercedes Benz announced in July 2017 that it will discontinue its B-Class Electric Drive car (only 744 sold in 2017) to focus on the upcoming EQ brand of electrified vehicles.
7. Introduced in December 2016, the Chevy Bolt is one of the most popular BEVs due to its range and affordability. We are using the Chevy Equinox as the gas car comparison based on hp, weight and ratings.
8. Honda clarity was first introduced as a hydrogen fuel cell vehicle in California at $369/mth for a 36-month lease. The electric version launched in July 2017 and the PHEV was launched in November 2017.
9. The Hyundai Ioniq Electric and PHEV is only available California for now. It was launched in March 2017.
10. In August 2017, it was announced that the Mitsubishi i-MiEV will no longer be sold in North America.
11. The 2018 Nissan Leaf has improved its performance with a 40kWh battery (compared to a 30kWh battery in previous models) that will increase range to 376km. We are using the Nissan Juke as an equivalent gas car.
12. Tesla's Model 3 has been experiencing widely reported production delays. A handful of models have been sold starting in July 2017.
13. Range for PHEV is based on the amount of range on the battery alone before the gas motor kicks in.
14. BMW i3 Rex is the the i3 pure electric model with a gas range extender that kicks in with only 34hp and can slow down to 45mph near the end of that additional range.
15. The Mini Countryman SE PHEV was introduced in June 2017
16. The Mitsubishi Outlander PHEV is unique in that it can act like a pure hybrid when the battery is fully charged. It was released in December 2017.
17. Volvo introduced the XC50 and the S90 in July 2017 and September 2017 respectively.

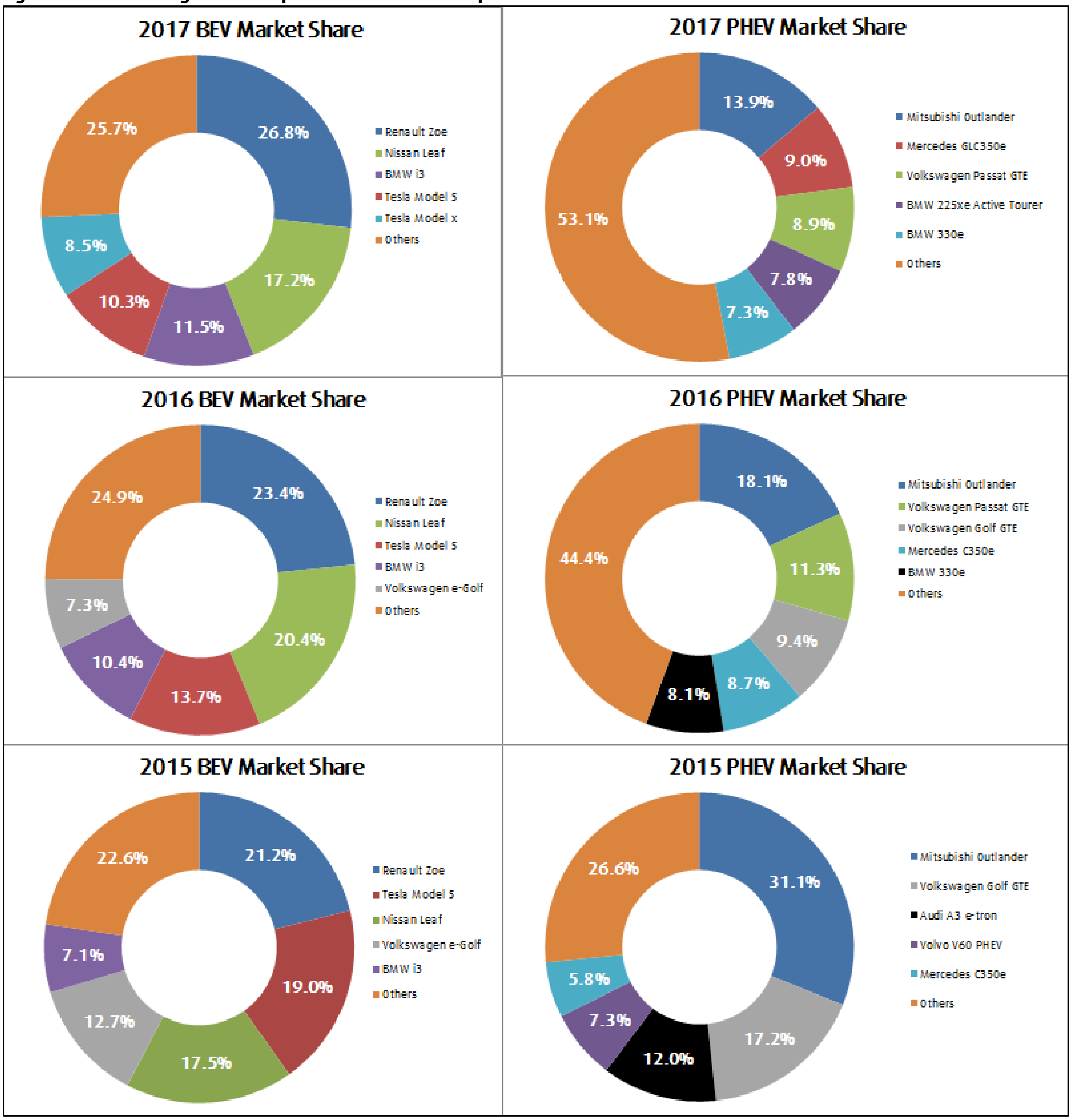
Sources: caranddriver.com, carsalesbase, plugndrive.ca, BMO Capital Markets

There Are More EV Models Exclusive to European Market

The European market (EU+Switzerland+Norway) is the second largest EV market (after China) and has made a number of announcements over the past year, all of which imply there will be more aggressive regulatory measures in the coming years. The country leading the European market by far is Norway with 39.2% of the market in 2017, and as such, continues to be our case study on EV market uptake globally. Others include Iceland (14.1%), Sweden (5.28%), Belgium (2.68%), and Finland (2.57%), with other EU countries around the 1-2% mark.

In this market, the popular model is the Europe-only model by Renault, called the Zoe. The overall makeup of the market has changed little since 2015. However, this is not the case in individual countries, as in many cases, models come and go. Therefore, while the overall picture is useful, it is made up of individual markets that have very different incentives.

Figure 30: Little Change in the Popular EV Models in Europe



Source: EAFO, BMO Capital Markets

BMW i3 and VW e-Golf dominate the market while Tesla's Model S market share is being replaced by its Model X

The European market also has a number of models exclusive to that market that may or may not be available in each country. Since 2015, the EU market has been dominated by the Renault Zoe, Nissan Leaf, BMW i3, and Tesla at the top, while the Volkswagen e-Golf has maintained a respectable ~7%. However, there are many models that are around a 5% share and below that keep coming into and going from the market.

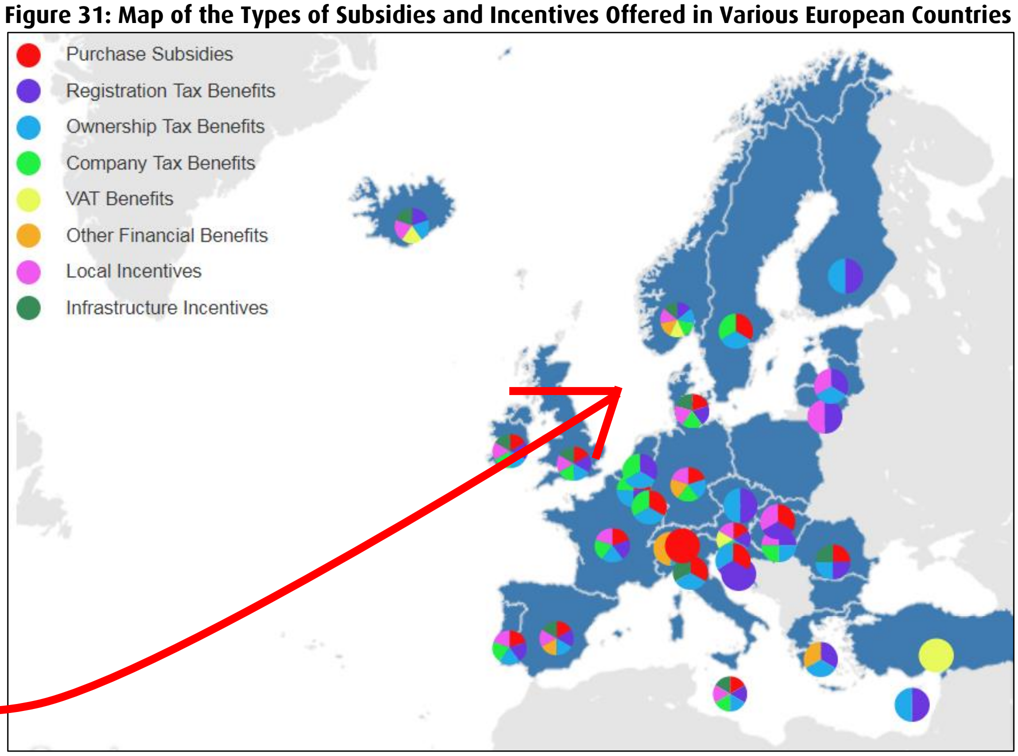
Norway Remains the Beacon for the European Market

Norway has the lead in Europe at 34.7% market share…

…likely as it has the most comprehensive subsidy plan in the world and vast charging infrastructure

Norway's success in deploying EVs onto the market is tied to having the most comprehensive EV subsidy plan in the world (e.g., access to bus lanes, free municipal parking, free electricity for normal charging (3.6kW), no purchase price, VAT or import taxes, exemptions from ferry tolls, etc.). The country also has an extensive public charging infrastructure with 2,058 fast chargers meaning that there are 393 fast chargers per million people. **While we believe subsidies and incentives are very important, we also believe that infrastructure investments such as these indicate a more aggressive push for EV adoption at the national level.**

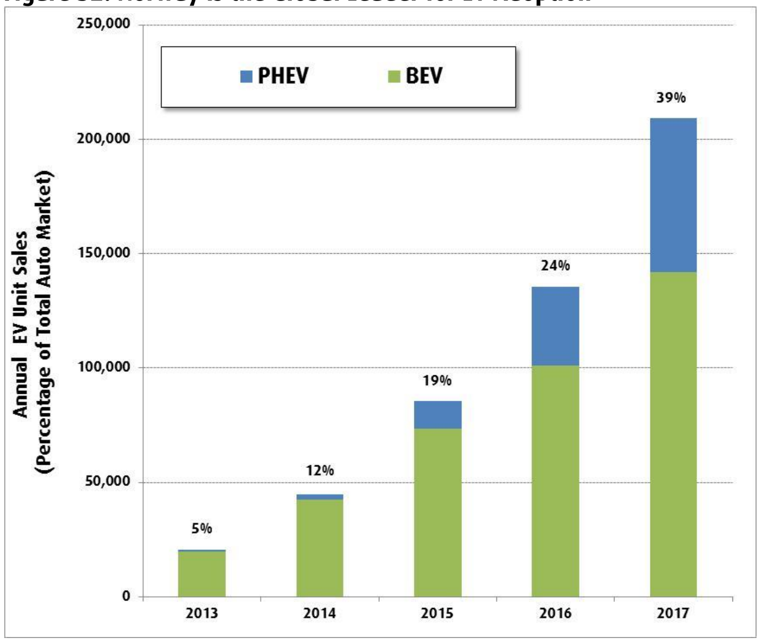
Figure 31: Map of the Types of Subsidies and Incentives Offered in Various European Countries



Source: EAFO

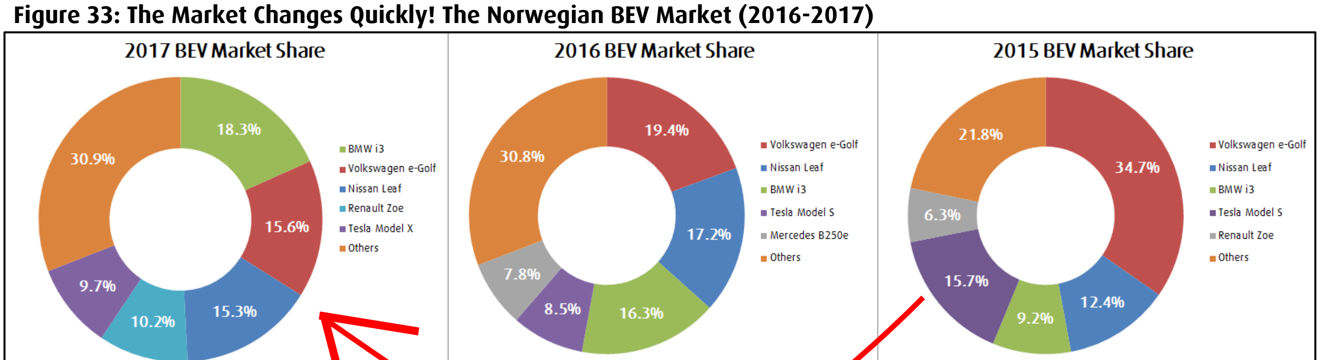
In Norway, BEVs, PHEVs and straight hybrids made up half of automobile sales last year. BEVs alone make up 20.8% of this number and the country is by far leading the charge in the EV market. In 2017, the top-selling models in this market were the BMW i3 (18.3%), the Volkswagen e-Golf (15.6%), the Nissan Leaf (15.3%), the Renault Zoe (10.2%) and Tesla's Model X (9.7%). The top five EV brands in this market have not changed much since 2015, but have been jockeying, and continue to duke it out for the top spot. At first the Nissan Leaf and Tesla's Model S owned the market, with 2013 share of 55.9% and 24.1%, respectively. The dominance of these two brands started to wane the following year. The Model S was replaced by the Model X when it came out and both Tesla and Nissan lost market share to the BMW i3 and the Volkswagen e-Golf. On the PHEV side, the Mitsubishi Outlander PHEV has been in the top spot since its 2014.

Figure 32: Norway Is the Global Leader for EV Adoption



Source: Norsk Elbilforening, BMO Capital Markets

Figure 33: The Market Changes Quickly! The Norwegian BEV Market (2016-2017)



Source: EAFO, BMO Capital Markets

Renault Zoe Is Top of the Market, But for How Long?

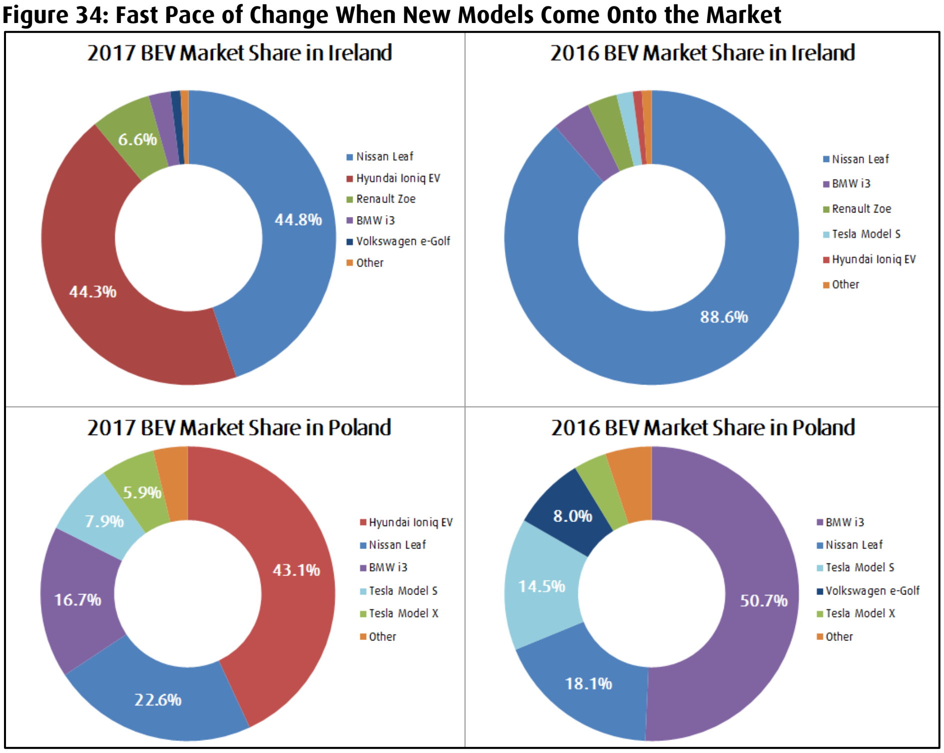
The top spot since 2015 – at 26.8% market share. The most important model in the EU market is Renault's Zoe, which has been in the top spot since 2015 and had a record 26.8% market share in 2017. This is likely due to its increasing popularity in France where it has represented over 60% of the market since its 2013 debut. In 2017, France topped the number of new BEV registrations by country at 22.4% compared to 21.9% for Norway.

Main competitors – Nissan Leaf and BMW i3. While its main competitor remains the Nissan Leaf, the BMW i3 has also been giving the Zoe a run for its money. Even though Zoe maintained a 24.3% market share in Germany (BMW home country with the i3 placing second at 13%), the BMW i3 is proving formidable taking the top spot 18.3% in of Norway where the Zoe came in fourth at 10.2%. The i3 is also the only upscale BEV in markets such as Greece (90.9%), Croatia (50.0%), and Turkey (82.4%), and tops well-segmented markets such as the Czech Republic (26.4%). At one point, the Nissan Leaf was the only BEV option for the value-oriented consumer and it has maintained its second place status for over the past two years with 17.2% in 2017 and 20.4% in 2016. We believe that its November 2017 year-over-year drop of 50% (1,172 million in 2016 vs 622 million in 2017) in new car registrations is due to the anticipated 2018 model, which has increased range and performance enhancements.

Hyundai Ioniq could become a fierce competitor. Early indications also show that the Hyundai Ioniq could become a fierce competitor for both the Nissan Leaf and the Zoe as it expands to more EU markets. The Hyundai Ioniq was introduced in some EU markets in late 2016. Since then, it has bumped the Nissan Leaf, cutting its whopping 89.6% market share in Ireland in 2016 by half to 44.8% in 2017 vs. 44.3% for the Ioniq. The Hyundai Ioniq has already tossed the BMW i3 out of the top spot in the Polish market, where it enjoyed a 50.7% market share in 2016, only to be cut to 16.7% (or third place) in 2017.

The introduction of the Hyundai Ioniq EV drastically changed the Irish and Polish markets within a year

Figure 34: Fast Pace of Change When New Models Come Onto the Market



Source: EAFO, BMO Capital Markets

Tesla's pricier EV option does well in countries with high GDP per capita. Tesla continues to be king in the Netherlands with a 2017 market share of 37.8% (down from its high of 50.8% in 2014, but still holding strong). It also has stayed at the top of the Swiss market with a 2017 market share 0f 52.1%. In our view, Tesla’s pricier EV option still tends to do well in European countries with a high GDP per capita; however, its Model 3 is likely to become a strong contender in the moderately priced segment.

From our analysis, the message is clear — dominate a market one year and be obliterated the next. We believe that with Hyundai’s intentions to expand the Ioniq EV and the introduction of the new 2018 Nissan Leaf model, the make-up of the 2018 BEV space in Europe could look drastically different. In addition, the Opel Ampera-e is a rebranded clone of the Chevy Bolt that just hit the market in April 2017 and has sold an impressive 2,000 units so far. Given the market uptake seen in North America, it is also one that we will be watching closely. Furthermore, Kia’s Niro hybrid sold an impressive 42,534 units since its May 2016 debut and there could be a similar uptake with the PHEV version of the Niro in 2018.

We believe the **Renault Zoe, the 2018 Nissan Leaf, the Hyundai Ioniq EV and the BMW i3 are the ones to watch in this market,** and we will see if Tesla can regain some of its market share when it launches the Model 3. See Figure 35 overleaf.

Figure 35: Renault, Nissan, Hyundai and BMW Are the Ones to Watch

Battery Electric Cars (BEVs)		Pack Size		NEDC e-Range [1]		E.U. Units Registered			Base Price
Brand	Model	(kWh)	hp	(miles)	(km)	2015	2016	2017	(€)
BMW	**i3**	**33**	**170**	**186**	**300**	**11,851**	**14,999**	**21,010**	**38,399**
Citroen [2]	C-Zero *	17	63	99	160	1,075	1,780	1,105	16,990
Citroen	E-Berlingo *	23	67	106	170	268	473	981	34,968
Citroen	E-Mehari *	30	—	124	200	—	569	353	27,000
Hyundai	**Ioniq Electric** [4]	**28**	**105**	**155**	**250**	**—**	**1,143**	**6,117**	**26,945**
Kia	Soul Electric	31	105	130	210	5,812	4,484	5,552	33,700
Mercedes-Benz	B250e (B-Class)	36	84	124	200	2,795	3,508	2,028	40,649
Mitsubishi	i-MieV	16	66	99	160	708	484	447	22,200
NEV (SAAB)	NEVS 9-3 [5]	—	—	124	200	—	—	—	—
Nissan	**Leaf**	**30**	**147**	**155**	**250**	**15,303**	**18,210**	**16,832**	**19,450**
Nissan	e-NV200 [6] *	24	107	106	171	2,448	3,739	3,270	33,273
Opel	Ampera-e [7] *	60	200	323	520	—	—	1,918	45,734
Peugeot	iOn *	16	63	99	160	1,566	1,881	1,544	18,990
Renault	Kangoo ZE *	33	60	168	270	4,114	3,688	4,100	24,000
Renault	**Zoe ***	**41**	**87**	**249**	**400**	**18,469**	**21,240**	**30,134**	**22,490**
Tesla	**Model S**	**90**	**532**	**383**	**613**	**8,841**	**11,564**	**16,026**	**69,019**
Tesla	**Model X** [8]	**90**	**532**	**285**	**542**	**—**	**3,683**	**11,877**	**156,100**
Tesla	**Model 3**	**65**	**271**	**—**	**—**	**—**	**—**	**—**	**35,000**
Smart [9]	Fortwo ED	18	80	90	145	2,013	323	5,191	17,560
Volkswagen	**e-Golf**	**36**	**134**	**118**	**190**	**11,124**	**6,657**	**12,895**	**34,900**
Volkswagen	eUP! *	18.7	82	99	160	2,769	2,557	3,054	25,475
	Average	37	156	161	264	5,944	5,610	7,602	37,142
					Total	89,156	100,982	144,434	
					CAGR	—	13.3%	43.0%	

Plug-In Hybrids (PHEV)		Pack Size		NEDC e-Range [1]		E.U. Units Registered			Base Price
Brand	Model	(kWh)	hp	(miles)	(km)	2015	2016	2017	(€)
Audi	A3 e-tron	9	204	31	50	11,711	6,908	8,356	30,997
BMW	i8	7	357	15	24	2,056	1,517	988	109,000
BMW	225xe Active Tourer *	8	88	15	24	266	5,937	10,805	58,490
BMW	330e	8	180	25	40	89	8,695	10,117	32,590
BMW	530e	9	180	19	31	—	—	6,143	64,890
BMW	X5 xDrive 40e	9	240	19	31	1,649	5,309	5,944	68,400
Kia	**Niro PHEV** [10] *	**9**	—	**34**	**55**	—	—	—	30,000
Kia	Optima Sportwagon PHEV *	11	67	38	61	—	—	—	32,645
Mercedes	C350e	6	275	19	30	5,858	10,233	6,861	58,450
Mercedes	GLC350e *	—	315	21	34	—	1,704	11,249	78,900
Mini	Countrymen SE 4	8	221	25	41	—	—	—	31,585
Mitsubishi	Outlander PHEV	12	197	32	52	31,275	21,343	19,189	32,325
Porsche	Cayenne PHEV	11	416	31	50	3,350	2,955	n.a.	86,966
Toyota	Prius Plus	9	121	31	50	7,120	6,718	7,379	34,930
Volkswagen	Golf GTE *	9	204	31	50	17,258	11,106	9,267	35,990
Volkswagen	Passat GTE *	10	218	31	50	4,819	13,332	13,599	43,888
Volvo	XC90 PHEV	10	400	16	26	2,859	9,587	7,847	65,000
Volvo	S90 T8 [11]	9	400	22	35	—	—	—	59,337
Volvo	V60 PHEV *	811	400	31	50	6,952	4,159	n.a.	46,895
	Average	54	249	26	41	7,328	7,822	9,057	52,699
					Total	95,262	109,503	117,744	
					CAGR	—	14.9%	7.5%	

* Denotes European models not available in North America

1. The New European Driving Cycle (NEDC) is designed to assess range in EVs in the EU (varies with driving habits and climate)
2. Citroen announced in Spring 2017 that it will have new generation EVs in 2020.
3. The E-Berlingo is an electric van expected to be released in 2018.
4. The Hyundai Ioniq was introduced in Europe in June 2016 and comes with 3 different powertrains: BEV, PHEV and straight electric
5. NEVS announced in December 2017 that it will introduce an all electric version of the SAAB 9.3 sedan called NEVS 9-3 in 2018.
6. Nissan is in the process up upgrading the E-NV200 electric vac to increase the driving range by 60% to 174 miles.
7. Opel Ampera-e is the rebadged European version of the Chevrolet Bolt that was introduced in April 2017.
8. Tesla's Model X was introduced to the European Market in June 2016.
9. Smart announced in September 2017 that it will no longer produce ICE vehicles in 2019.
10. The Kia Niro PHEV was launched in December 2017. The Niro hybrid was launched in May 2016 selling 42,534 units so far.
11. Volvo S90 T8 PHEV was released in Europe in July 2017.

Source: carsalesbase, EAFO, WattEV2buy, Company Reports, BMO Capital Market

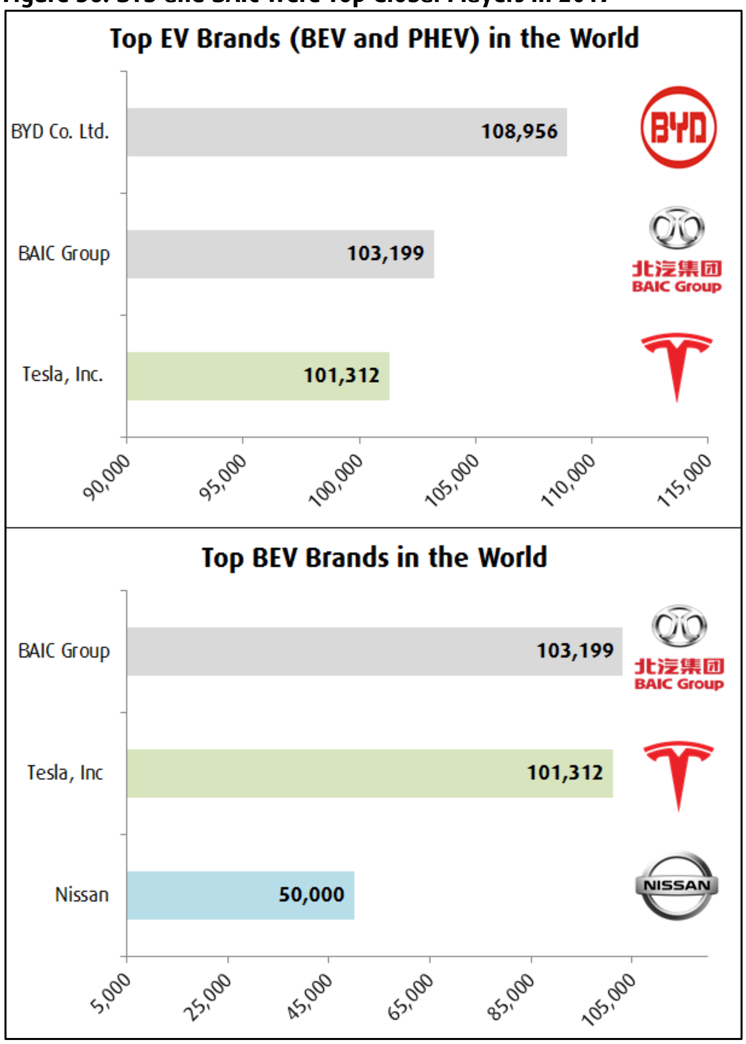
The Changing Chinese Market – EVs Represent 3.3% of the Auto Market

China has over 172 companies competing in the automotive space and regulations preclude foreign brand participation

Industry heavyweights in China are acquiring technologies from Western automakers, hiring experienced engineers from companies like Tesla and aligning established brands such GM or Volkswagen. Geely's story, and to a lesser extent BAIC, is certainly emblematic of this with multiple strategic acquisitions over the last two years. The message is clear: when it comes to the EV space, Chinese automakers are investing a significant amount of capital.

The Chinese market has evolved quite rapidly over the last year with an unprecedented number of new EV models. Over 600,000 units (BEV and PHEV) were sold in 2017, up 71% from 2016. Although there are not as many models earmarked for 2018 yet, we believe that announcements will increase leading up to the Beijing Motor Show at the end of April. For now, many established Chinese OEMs have a few models coming out as established brands, such as BAIC, BYD, Geely and Zotye, which have cumulatively set a sales target of around 4.5 million EV sales by 2020. Of the top 10 major EV companies in the world, six are based in China.

Figure 36: BYD and BAIC Were Top Global Players in 2017



Source: wattev2buy, BMO Capital Markets

China began to look into electrification in the early 2000s due to the increasing pollution associated with the growth of the automobile sector. Some companies, such as BYD, actually started out as lithium ion battery companies for portable devices. With the rapidly-changing landscape, we are looking at which companies to watch rather than merely looking at which EV models will gain the most market share. The Chinese market is very different than the North American and European markets in that there are 172 companies vying to dominate the automotive space, and some, such as BYD, have already established a global presence. Here, we are going to focus on three companies (a public, a state-owned and a private company) to convey the nuances of this market as well as the globalized view Chinese automakers appear to be taking.

Top Chinese Players – Making a Big Push in the EV Space

Chinese regulations favour domestic OEMs and most companies are also state owned, with BYD and Geely the exceptions. There are also many non-Chinese companies looking to get into the game as well, including big U.S. names such as Ford and GM, often form joint ventures with Chinese companies to market their brands to mainland China. Due to regulations, foreign brands on their own only make up 4% of the EV market with Tesla garnering half of that and therefore, many form partnerships with Chinese companies. For example, SAIC and GM formed a joint venture in 1997 while Ford and its partner Anhui Zotye Automotive announced in November 2017 its plans to invest $756 million in a joint venture to build EVs.

Figure 37: BYD and the Blue and White Detailing, is the Hallmark of China's EV Industry

Source: Evercharge.com

It is a fast-paced arena that is evolving quite quickly. Here is more detail about the dominant players in China's EV market:

Berkshire Hathaway is the 4th largest shareholder with an 8.25% stake

i. BYD Co Ltd. (SHE:002594)

BYD, an acronym for "Build Your Dreams," is the world's top producer of EVs in the world. While it has its roots as a mobile phone battery maker, a US$230 million investment (225 million shares) by MidAmerican Energy (a subsidiary of Berkshire Hathaway Energy) quickly changed its trajectory—it is now a key player in the EV market. It has grown into a strong global presence with 30 industrial parks globally and it is also the world's biggest battery manufacturer. BYD has preferred to invest in its own in-house lithium battery manufacturing plant, ensuring that its supply chain is fully controlled, and foregoing joint ventures or alliances traditionally seen in this space. BYD is also the largest electric bus manufacturer in China and also has a line of electric forklifts, tractors, and trucks, and is planning to aggressively expand its North American operations to take on Tesla. The company is flush with cash with ~ US$1.3 billion in its monetary fund.

BYD is one of the largest battery manufacturers in the world, with an extensive line of e-buses, e-trucks and monorail system

The most diversified in this space

BYD's success so far has been its ability to guide its R&D capabilities in a forward-thinking manner. Not only does BYD already have a few long-range delivery truck models (class 5, 6 and 8), but it is also taking its public transit focus one step further by introducing its SkyRail monorail system. Already installed in the cities of Shenzhen (October 2016) and Yinchuan (September 2017), the monorail system reportedly costs one-fifth that of a traditional monorail system and can be built in one-third the time it takes to build a traditional system. BYD has set up a US$940 million fund to expand its monorail system throughout China.

Figure 38: BYD's SkyRail Monorail System

Source: BYD

Localized manufacturing close to key markets. Although BYD is a global company, its core values insist that it localizes its manufacturing closer to key markets. It has a number of wholly-owned subsidiaries around the world and its 2017 initiatives have been an aggressive global push with activity on all the major continents.

BYD has already established manufacturing facilities in the U.S. and Europe with aggressive global push on all major continents

1. **U.S. Presence:** BYD Motors Inc. is a wholly-owned subsidiary of BYD that uses the catch phrase "The Official Sponsor of Mother Nature." The subsidiary already has a five year-old electric bus manufacturing facility in Lancaster, California, which was recently expanded to 450,000 square feet. The facility now has capacity to build 1,500 electric buses per year. This new production capacity could mean a 30% stake in the North American electric bus market. BYD also announced in early 2017 that it wants to be the first Chinese automaker to sell in the U.S. and is strategically positioning itself to launch in 2019-2020.

2. **Canadian Expansion:** In November 2017, BYD announced its intentions to build its first Canadian assembly plant near Toronto, Ontario, in anticipation of a surge in North American demand for electric trucks. The reason for its location is the wide, already-established distribution network, more lenient barriers to entry for Chinese products and a business environment conducive to electrification. In the same month, Loblaw Companies

Ltd. announced that it has pre-ordered 25 new Tesla trucks re-stating its intentions to electrify its fleet to meet internal goals of reducing its carbon footprint by 2030.

3. **South America:** At the Chinese Hi-tech Fair in November 2017, BYD announced that it signed a deal with the La Rioja province in Argentina to provide 50 electric buses over the next two years beating out five other bidders. Through its subsidiary, CTS Auto, BYD will be investing US$100 million to build a facility in Argentina to build them locally that is expected to be up and running by the end of 2018.

4. **Europe:** BYD Europe has its main office in the Netherlands and has already introduced its e6 electric sedan to key test markets including Russia, Spain and Switzerland. In April 2017, BYD completed a €20 million 710,000 square foot electric bus factory in Komàrom, Hungary. Once at full capacity, it is expected to produce 400 fully electric buses per year. It also acquired an 816,000 square foot factory in northern France and plans to open an EV factory in Monaco on a 50-hectare site to build electric cars, buses and trucks.

ii. BAIC Group

The BAIC group (Beijing Automotive Industry Holding Co.) is a state-owned holding company owned by the Beijing Municipal Government, which owns a number of OEMs and machine manufacturers. The company is in a joint venture to produce Hyundai and Mercedes cars for the Chinese market and owns a number of brands such as BAIC, BAW, Changhe, Foton, Huansu, Senova and Weiwang. In 2009, BAIC bought technology from Saab Automobile for $200 million, which gave the company the intellectual property rights to a number of older Saab models. This gave the company the platform it needed to create a number of models (i.e., a Jeep Wrangler clone), but more importantly, the technology launched its EV unit.

Its electric vehicle unit is called the Beijing Electric Vehicle Co. Ltd., known as BJEV, and is the second largest EV (BEVs and PHEVs) manufacturer in China after BYD, and competes neck-and-neck with Tesla in the number of BEV units sold globally. The OEM unit was founded in 2009 and received its permit to make EVs in 2016. In 2017, its EC-series of EVs sold a whopping 78,079 units in China alone — 84% higher than second place Zhidou D2.

BAIC is expected to reverse-list its EV unit (BJEV) on the Shanghai Stock Exchange

On January 23, 2018, it was announced that BAIC will be listing its EV unit (BJEV) on the Shanghai Stock Exchange using an asset-swap program. This means that a BAIC subsidiary, ChengDu QianFeng Electronics Co., Ltd. will buy BJEV and list the combined unit on the stock exchange. This is in line with its plans to consolidate similar businesses in an effort to cut costs.

iii. Zhejiang Geely Holding Group Co., Ltd.

The trend in the Chinese auto industry is to either align with or acquire leading Western brands. Geely is certainly aggressively pushing in all areas of the EV market and taking this globalized approach to building its EV business.

One of the few companies without ties to the state. Zhejiang Geely Holding Group Co., Ltd. (private), established 31 years ago, is one of the only companies without ties to the state. Geely is a private holding company that sells cars under the Volvo (cars division was acquired in 2010), Link & Co (founded in 2016) and Geely Auto brands. In May 2017, Geely acquired a 49.9% stake in the Malaysian auto company Proton and a 51% controlling stake in the famous British sports car company Lotus Cars. It also owns commercial vehicle brands London Electric Vehicle Company and Yuan Cheng Auto (e-trucks and e-buses). In December 2017, Geely acquired an 8.2% stake in AB Volvo in order to access its semi-truck technology that has been made famous by the many viral ads. In addition, Geely has entered into a number of joint ventures that have involved the establishment of separate brands such as the ZHIDOU and Gleagle. It has also acquired Massachusetts-based start-up Terrafugia, which has been developing a flying car.

Its subsidiary, Geely Automobile Holdings Ltd. (SEHK: 175), is listed on the Hong Kong Stock Exchange and is part of the Hang Seng Index. We believe that the next two years will be very interesting for this company given these recent acquisitions and investment activities.

Figure 39: The Extensive Car Brands of Geely (Volvo, Link & Co and Geely Auto)

Source: atoblog, Link & Co, Geely Auto

Figure 40: Geely's Commercial Vehicles Including an Electric Version of London's Famous Taxi Cabs

Source: Autofocus, Geely, Volvo

Several U.S. EV start-ups have received a substantial amount of Chinese capital

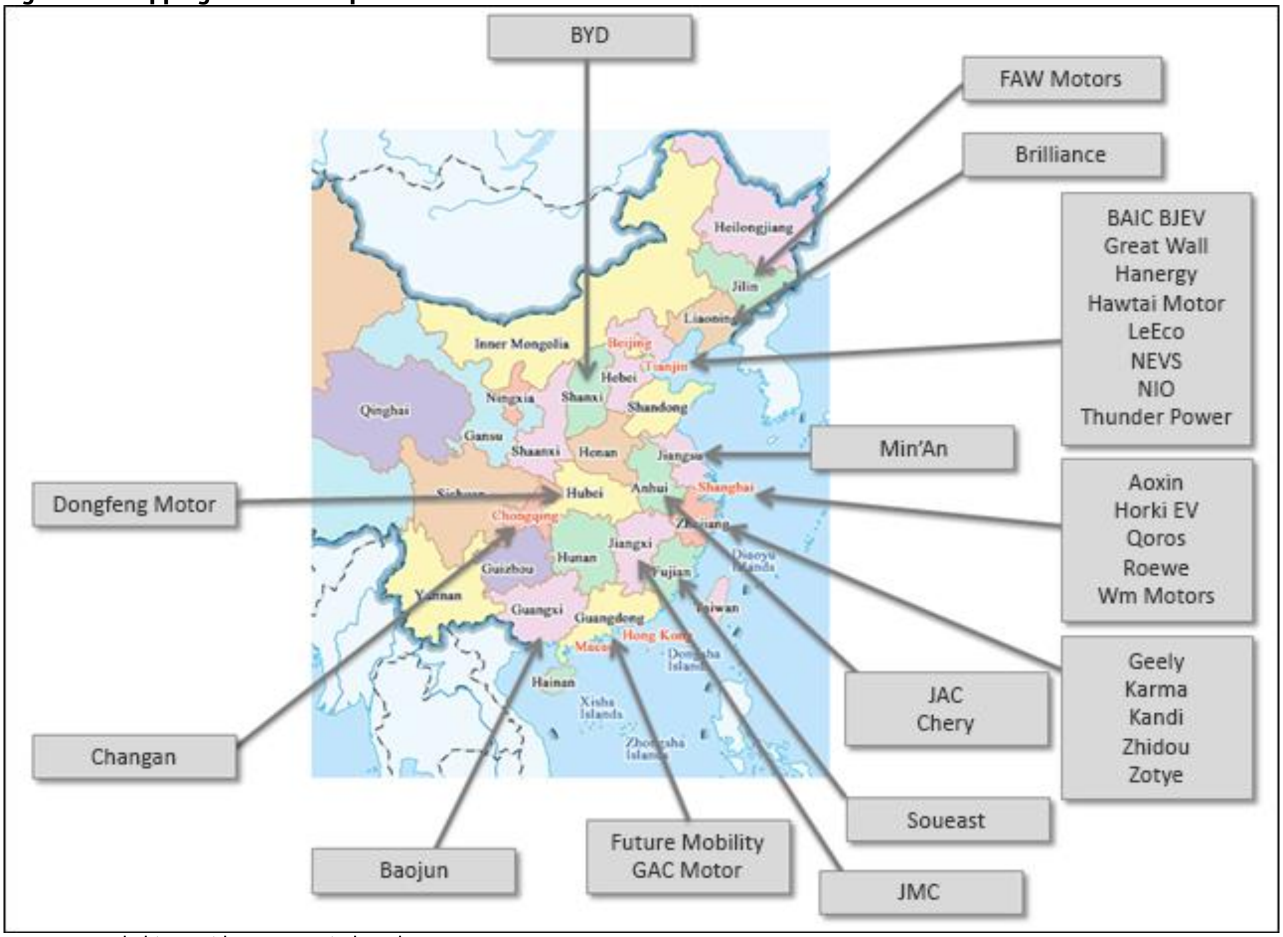
Newcomers in the Chinese Market – Looking to Make a Dent

There is also a new breed of OEMs vying for a shot at this market with many receiving e-permits over the last two years. Relative newcomers we are watching include NIO (private), London EV Co. (a subsidiary of Geely), Kandi Technologies (NASDAQ: KNDI), Min'An Electric Automobile Co. (private), South East (Fujian) Motor Co., Ltd. (private), and Thunder Power Holding Limited (private) to see if they can grab a foothold into this rapidly-expanding market. Furthermore, the defunct company, Saab Automobile, has been reinvented as the National Electric Vehicle Sweden AB under the NEVS brand under Chinese ownership. We are also seeing several U.S. start-ups that have received substantial capital from China to introduce new EVs on the market. These include California–based Lucid Motors (formerly Atieva), Detroit Electric Inc., and Faraday Future (a subsidiary of LeEco). In 2018, Toyota plans to start rolling out its EV strategy to in an effort to play "catch up" to competitors such as Tesla and GM by introducing 10 pure EV models in China by 2020.

Toyota ready to roll out its BEV line in China to test the waters

A brand long associated with pioneering the EV space, Toyota has had a bumpy experience in the BEV segment of the industry. Back in 2012, it scrapped plans for an electric minicar and has since been quiet about its future plans. However, its strategy now is intriguing as the China rollout could be the testing ground necessary for the company to develop a winning global strategy. Clearly, Toyota cannot be counted out, yet.

Figure 41: Mapping Out the Complex Chinese EV Market



Source: Travel China Guide, BMO Capital Markets

Figure 42: The Chinese BEV Market Is Vast – BYD, BAIC and Geely Are the Ones to Watch

Battery Electric Cars (BEVS)		Pack Size	Cathode		NEDC Range		EV Car Registrations			Base	
Brand	**Model**	**(kWh)**	**Type**	**hp**	**(miles)**	**(km)**	**2015**	**2016**	**2017**	**Price(¥)**	**Introduced**
BAIC	EC-Series	20	NMC	31	112	180	—	—	**78,079**	151,800	2017
BAIC	Arcfox Lite EV	16	—	49	93	150	—	—	—	140,800	2017-2018
BAIC	EU Series	41	NMC	136	163	260	—	18,805	13,158	254,900	2016
BAIC	EX 260	39	NMC	72	156	251	—	—	—	192,900	2017
BAIC	EH300EV	55	—	136	188	300	—	—	—	345,800	2018
BAIC	ET400[3]	53	—	72	217	350	—	—	—	—	2018
Baojun	E100[4]	14.9	—	39	96	155	—	—	11,420	93,900	2017
BYD	e6	82	LFP	107	240	386	7,029	20,605	10,023	309,800	2009
BYD	e5	48	LFP	215	132	212	1,426	15,639	23,601	195,900	2016
BYD	QIN EV	37	LFP	303	188	300	—	10,182	4,873	259,800	2016
BYD	Song EV	48	LFP	218	188	300	—	—	—	265,900	2017
Citroen[5]	E-Elysee	—	—	115	—	—	—	—	—	—	2018
Changan	Eado Electric	31			96	154		4,839		234,900	2015
Changan	Benni Electric	23	NMC	75	113	182	—	—	14,549	100,000	2016
Changan	Benni Mini-e-EV	17	NMC	—	95	152	—	—	—	82,800	2018
Chery	eQ[6]	22	LFP	57	120	200	7,269	16,017	27,444	165,900	2014
Chery	Arrizo 5e EV	49	NMC	122	219	351	—	—	—	212,800	2018
Chery	eQ1	18.6			113	180	—	—	2,695	155,900	2017
Chery	Tiggo3xe EV SUV	49		122	351	219	—	—	—	—	2018
Denza	EV	63	LFP		221	353	2,888	2,287	4,685	369,000	2014
Dongfeng[7]	Fensheng E30L	18	LFP		81	130	511	680	135	156,800	2015
Dongfeng	E70	49	—	120	219	351	—	—	—	212,800	2017
GAC	GE3	46	NMC	180	238	381	—	—	1,762	222,800	2017
Geely	Emgrand EV	41	LFP	127	158	253	—	17,181	23,324	—	2016
Geely	Dorsett GS Cross		NMC	163	221	353					2017
Geely	Zhidou D2	15	LFP	—	72	116	3,777	9,091	42,323	158,800	2015
Hawtai	E80 (formerly E70)	39		109	143	230	17,122	10,305	14,766	186,500	2016
Hawtai	EV160	21	NMC	41	97	155	—	—	11,823	102,800	mid 2017
Hawtai	XEV260	50	—	106	162	260	—	—	—	—	2018
JAC Motors	iEV6s	22	LFP		106	170	—	6,327	28,262	12,850	late 2016
Jiangling/JMC	E100	15	—	27	95	152	—	676	15,491	120,800	2016
Jiangling/JMC	E200	20	NMC	40	95	151	—	951	16,247	132,800	2016
Jiangling/JMC	E160	20	NMC	48	95	152	—	—	1,596	136,800	2017
Kandi	K12 Hawk EV	20	NMC	47	95	153	—	1,349	7,858	158,000	2015
Kandi	K17As Cyclone	20	LFP	47	84	151	—	1,896	3,648	164,800	2017
Zotye	E200	25		24	132	212	—	13,154	16,751		2016
Zotye	Zhima e30	18	—	24	94	150	572	3,471	5,516	119,800	2016
Zotye	Cloud EV	18	NMC	36	125	200	15,467	16,417	11,038	108,800	2015
	Average	**33**		**97**	**146**	**226**		**8,941**	**15,643**	**178,321**	**2017**

1. YTD as of November 30, 2017
2. Chery claims that the Arrizo 5e has a range of 410 km on a single charge. Will be releasing EPA and NEDC standards soon.
3. Brilliance Auto Group holds a 43% holding in BMW Brilliance which distributes BMW models in China
4. Baojun (SAIC/GM/Wuling JV) E100 is GMs tiny, two seater EV for China. It was launched in September 2017.
5. Citroen is in a JV with Donfeng.
6. The Chery eQ replaced a previous model (QQ3 EV) that used lead-acid batteries.
7. Dongfeng is expected to release 5 new models in 2018

Source: Company Reports, EV Sales Blog, ChinaAutoWeb, WattEV2Buy.com, BMO Capital Markets

Part II – The Science Behind the Numbers

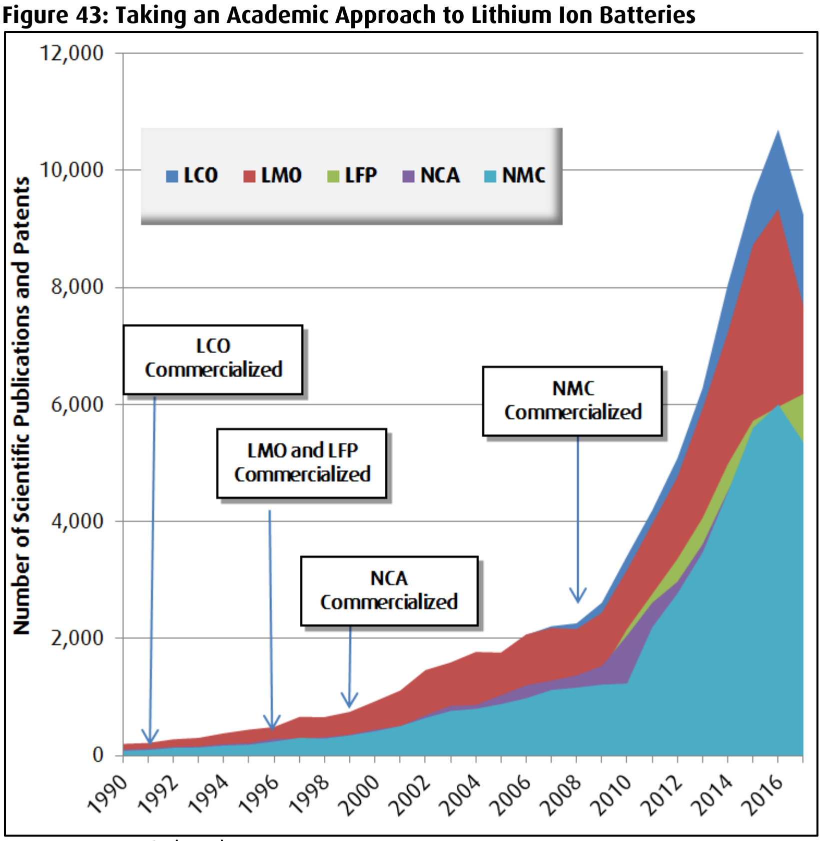
The battery industry is touting a lithium ion battery chemistry called NMC811 as the "next big thing." However, the use of this chemistry has stability risks that are not easy to alleviate. Furthermore, the capacity loss seen in experiments with as little as 100 cycles makes us reasonably skeptical that this chemistry will be the game changer over the next five years. However, when we looked at the scientific literature on the battery currently in Tesla's Models S and X, we concluded that we would probably have been just as skeptical about that chemistry as well. Therefore, we are optimistic that the technical challenges will be overcome, but not in the timeframe many currently predict.

Highly competitive and secretive space. Given the competitiveness of the EV space, the battery manufacturers do not readily show their hand. Instead, they prefer proclamations such as the announcement LG Chem made that it will introduce an NCM811 battery (a complicated chemistry with high energy) sometime this year. The secretiveness surely makes it difficult to get a handle on what is really going on. The automotive industry likely has confidentiality agreements in place.

Therefore, we decided to take an approach that complements the extensive industry analysis by the European Alternative Fuels Observatory and the International Energy Agency with an intense review of the scientific literature. We got up to speed on our electrochemistry, scoured the extensive amount of peer-reviewed journals that have been published on this technology and engaged chemists to back up our assumptions.

The industry focus is on improving the energy density (capacity) and reducing the cost of the NMC battery

Figure 43: Taking an Academic Approach to Lithium Ion Batteries



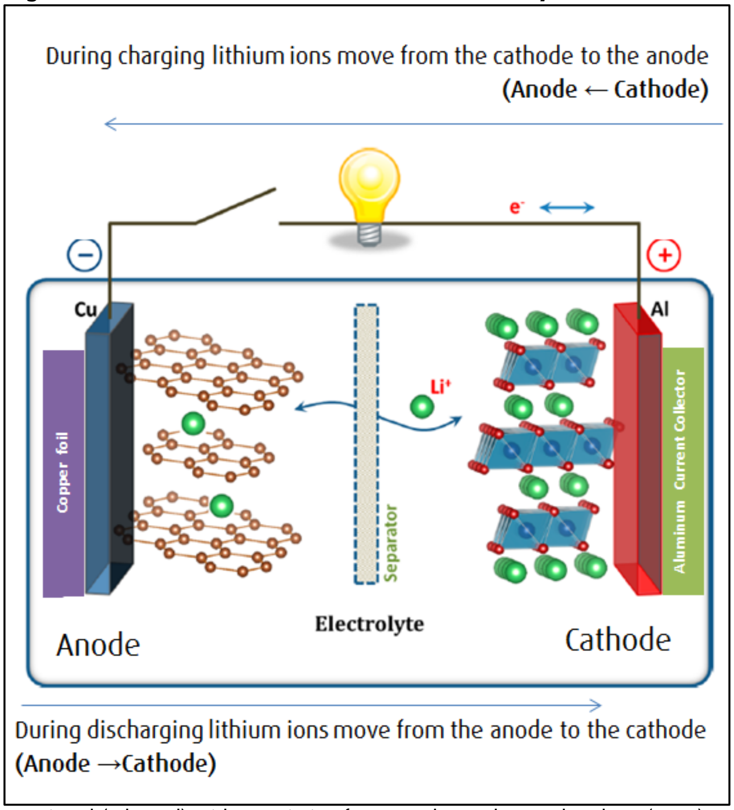
Source: BMO Capital Markets

In this section, we summarize our conclusions from Part III of this report titled *A Very Deep Dive on Cathode Chemistry.*

The Term "Lithium-Ion Battery" Describes a Number of Different Chemistries

The "lithium ion battery" encompasses a number of chemistries where lithium ions move back and forth between the electrodes (cathode ↔ anode) in a process often referred to as a "rocking chair" mechanism.

Figure 44: ALL Lithium Ion Batteries Work This Way



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Battery performance is primarily a function of the anode and the cathode to accept and release lithium ions

Performance of the battery is *primarily a function of the ability of the cathode and anode to accept and release lithium ions*. This means that power and time between cycles is largely dependent on the amount of reversible lithium ions (or the lithium ions that can be accepted and released) and the kinds of materials in the electrodes. **Typically, the materials are chosen to amplify this interaction as well as ensure that the lithium ions *remain reversible*.**

LCO, LMO, LFP, NMC and NCA are all different kinds of lithium batteries and describe the principal materials in the cathode

There are a number of different chemistries used within lithium batteries and these types *are named after the principal elements used in the cathode*. For example, the main composition of batteries used in laptops, tablets and cellphones is a lithium cobalt oxide cathode or an LCO battery. Other transition metals used in the cathode include nickel (Ni), manganese (Mn) and iron (Fe). Either used alone or in conjunction with one another, the main chemistries on the market today are summarized in the next two tables.

Figure 45: Main Commercially Available Lithium Ion Battery Chemistries

LCO: Lithium Cobalt Oxide	• Used primarily in portable electronics (cell phones, laptops, cameras, etc.). • Limiting factors such as low thermal stability (low safety) and high cost makes it unappealing for the EV industry.
LFP: Lithium Iron Phosphate	• Known for its thermal stability (high safety), LFPs have a low energy density (capacity) compared to other cathode chemistries. • LFPs are used in most Chinese EVs today, because of the availability of iron deposits within the country. However, due to its regulatory push to favour battery chemistries with increased energy density, major Chinese EV manufacturers (BAIC, BYD, Chery, Zotye) have expressed plans to switch from LFP to the NMC cathodes. However, the need to rely on outside sources and therefore, international cobalt prices, may make the switch problematic.
LMO: Lithium Manganese Oxide	• While LMOs are generally much safer than other cathodes, they have a much shorter lifespan. In order to enhance its long-term performance, it is usually blended with NMC chemistry or aluminum. • LMO-NMC blends are found in the batteries of the older Nissan Leaf models due to their cost advantages, but Nissan is also expected to switch to a pure NMC cathode in its second generation models.
NMC: Lithium Nickel Manganese Cobalt Oxide	• **The NMC cathode is the current focus of battery designers and researchers.** The goal here is to reduce overall costs by reducing cobalt content. • **A major concern is that the higher the nickel content used, the better the energy density, but the more unstable the battery.**
NCA: Lithium Nickel Cobalt Aluminum Oxide	• The NCA chemistry is most notably used in Tesla/Panasonic batteries so NCA potential is somewhat tied to Tesla's prospects. • It is similar to the NMC chemistries that have increased nickel content in many ways, but is more costly and has some safety issues that make it less attractive for more reasonably-priced EVs as considerable costs must be allocated to the battery management system.

Source: Battery University, BMO Capital Markets

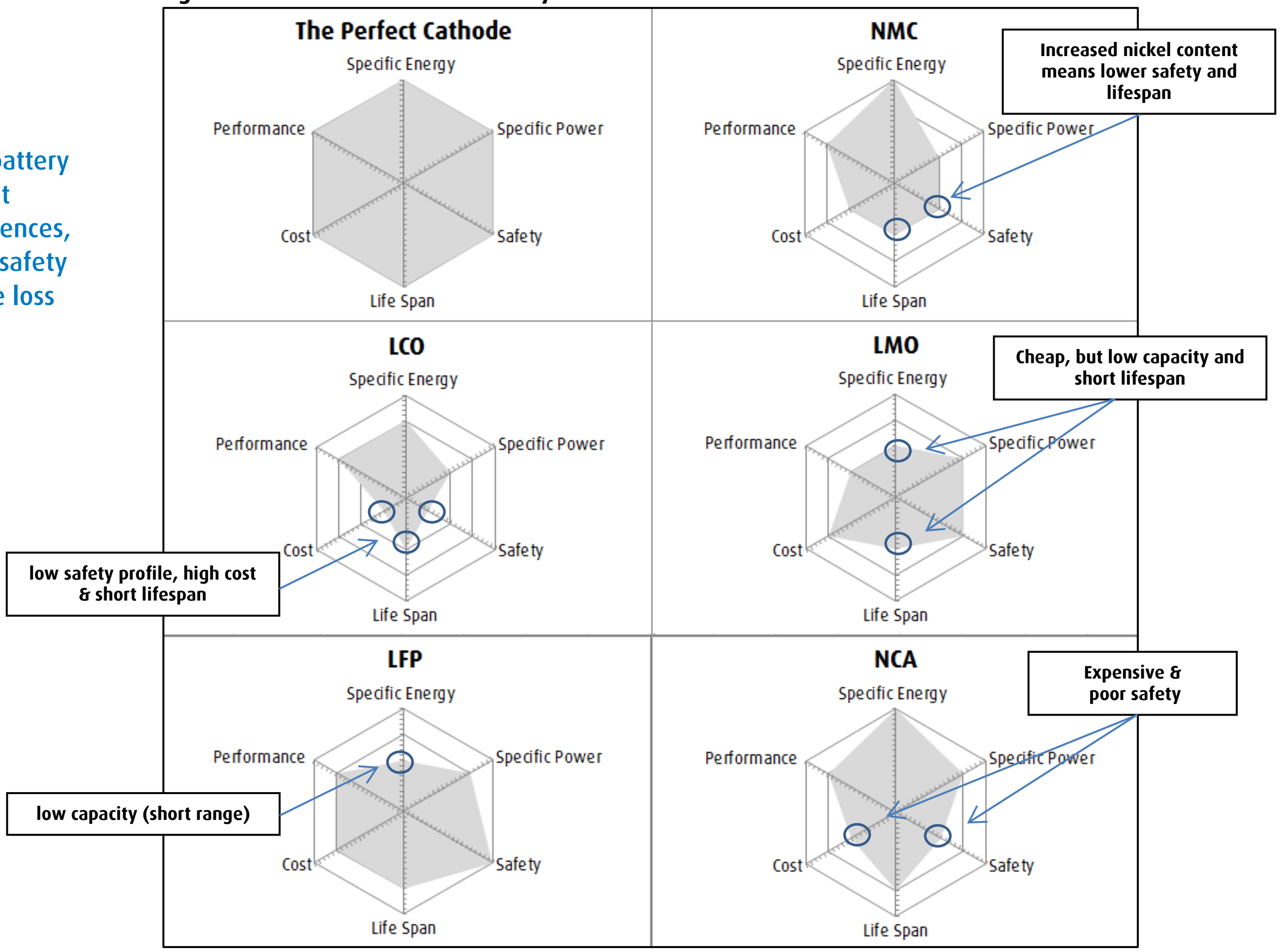
In order to penetrate the mass market, costs and performance need to be improved

We believe that despite the more rapid uptake in technology (steeper S-curves now compared to 50 years ago), lithium ion batteries will remain the main power storage method for at least another five to 10 years. Even then, we believe improvements to the chemistry will continue rather than a complete overhaul of the power sources in EVs, especially given the costs of implementing charging infrastructures. The literature is clear that the techniques to optimize cell design, such as packing density and battery structure, have advanced to a point where there is little room for improvement. Therefore, the industry is largely focused on changing the internal electrochemistry (mainly improving the electrodes and the electrolyte) and in the short term, is focused **on improving the structure and chemistry of the cathode.**

Quite simply, changing the chemical parameters has a variety of implications that can affect performance and safety making it difficult to manage the system. For example, manganese tends to degrade much faster that nickel and cobalt (especially in high temperatures) and is the principal reason why the industry has moved away from manganese-only LMOs. Cobalt-only LCOs may be fine for smartphone applications and laptops, but its reactivity in overcharging and high charge situations makes it dangerous for EV applications. It is also the reason why *smart luggage with* *non-removable batteries* has been banned from most airlines as checked baggage because they can be combustible in the lower storage compartments and the grounding of the Boeing 787 Dreamliner fleet. All these cathodes have trade-offs that are not easily remedied and the perfect cathode chemistry remains highly elusive.

Changes to the battery chemistry are not without consequences, such as reduced safety and performance loss

Figure 46: Perfect Cathode vs. Reality → The Trade Offs Between Lithium Batteries



Source: Battery University, Liu *et al.* (2017), BMO Capital Markets

Specific Energy (Wh/kg): Indicates the amount of energy available for the vehicle to work and determines the weight required to achieve a certain range. It is also referred to as capacity since the available energy determines the amount of range that the vehicle can go between charges. LFP and LMOs have a reduced range between charges than either NCA and NMC.

Specific Power (W/kg): The maximum available power available to the vehicle. The metric is equivalent to horsepower (HP) per weight in conventional vehicles.

Safety: Low thermal stability refers to the exothermic release of oxygen when a lithium metal oxide cathode is heated above a certain point, resulting in a thermal runaway reaction that can lead to fire. It is a key measurement for safety.

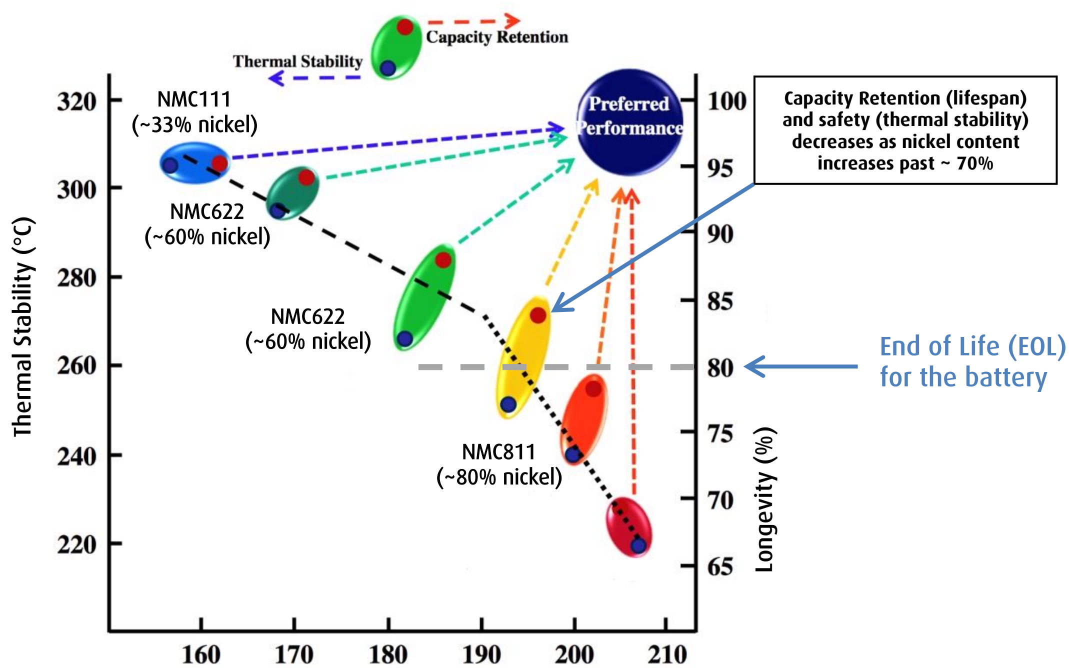
Figure 47: NMC Is Emerging as the Favourite Given Better Energy Density at a Reduced Cost, But Has Safety Issues

	LCO	LFP	LMO	NCA	NMC[1]
Cathode Elements	Cobalt	Iron	Manganese	Nickel Cobalt Aluminum	Nickel Manganese Cobalt
Chemical Formula	$LiCoO_2$	$LiFePO_4$	$LiMnO_2$	$LiNiCoAlO_2$	$Li(NiMnCo)O_2$
Cost (per kWh)	\$250-450	\$400-\$1200	\$400-\$900	\$600-\$1000	\$500-\$900
Specific Energy (Wh/kg) (Capacity)	150-200	90-120	100-150	200-260	NMC811:270 NMC622:225 NMC532:205 NMC111:199
Power Density Weight (W/kg) Volume (W/L)	600 1200-3000	1400-2000 4500	1000 2000	1500-1900 4000-5000	500-3000 6500
Thermal Runaway (°C)	150 (Least Stable with a full charge promoting thermal runaway)	270 (Most Stable even when fully charged)	250 (Very Stable, but high charge promotes thermal runaway)	150 (Least Stable)	NMC111:305 NMC532:295 NMC622:265 NMC811:240
Safety	-	++	+	--	depends on nickel content
Cycle life[2] (lifespan)	500-1000 Depending on depth of discharge, load and temperature	1000-2000 Depends on depth of discharge and temperature	300-700 (very low) Depends on depth of discharge and temperature	500-1000 Depending on depth of discharge, load and temperature	1000-2000 Depends on depth of discharge and temperature
Year Introduced	1991	1996	1996	1999	2008

1. NMC cathode types vary by ratios of nickel(Ni), manganese(Mn) and cobalt (Co) content. For example, an NMC622 contains one atom formulated with 60%Ni, 20%Mn and 20% Co. In the industry and scientific literature NMC=NCM. The specific energy (capacity) increases with nickel content, however, the thermal stability decreases. A high charge promotes thermal runaway.
2. Cycle life represents the number of complete charges a battery can perform until it reaches its end-of-life (EOL) of 80% its initial capacity or a 100% increase in the internal resistance.

Sources: Battery University, Noh et al., 2013, Warner, 2015; BMO Capital Markets

Figure 48: The Reality of Increasing Nickel Content – Thermal Stability and Capacity Goes Down



Reprinted (adapted) from Journal of Power Sources, 233, Noh H., Youn, S., Yoon C. and Sun, Y. Comparison of the structural and electrochemical properties of layered $Li[Ni_xCo_yMn_z]O_2$ (x=1/3,0.5,0.6,0.7,0.8and 0.85) cathode material for lithium-ion batteries. p.121-130, 2013, with permission from Elsevier.

The NMC cathode contains nickel, manganese and cobalt in varying concentrations. For example, NCM111 would have equal parts (~33%) nickel, cobalt and manganese. Other combinations have more nickel content than either cobalt or manganese, and therefore, are referred to as "nickel-rich"

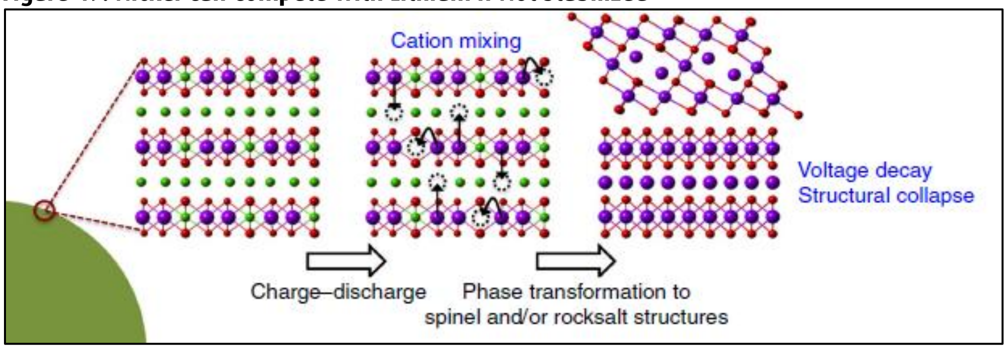
NMC cathodes. NMC532 would have 50% Ni, 30% Mn and 20% cobalt. Due to costs, the battery industry is trying to increase nickel content relative to cobalt. However, Figure 48 shows that as nickel increases, the thermal stability and the longevity decreases to the point where it is dangerous and economically unfeasible.

The Key Factor for Our Skepticism on NMC811

While Part III of this report is significantly more detailed, the gist of our analysis is that cobalt concentrations need to be maintained at around the ~20% level because cobalt stabilizes nickel. Through our analysis on nickel-only cathodes, nickel ions are the same atomic size as lithium ions and they compete with each other for space in the cathode. In a process called "cation mixing," nickel ions overtake lithium ions and eventually cause the cathode to become structurally distorted. The right amount of cobalt (but not too much) seems to stop nickel from competing like this.

As nickel (purple) competes with lithium (green) in the cathode until it deteriorates to the point it can't do its job

Figure 49: Nickel Can Compete With Lithium if Not Stabilized



Source: Kim, S, Cho, W., Zhang, X., Oshima, Y. and Choi, J. (2016). *A stable lithium-rich surface structure for lithium-rich layered cathode materials*. Nature Communications; DOI: 10.1038/nscomms13598.
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While we are skeptical, the intellectual and investment capital invested in NMC811 gives us hope. By many standards the NCA and NMC chemistries have similar issues because of the high nickel content. However, the NCA battery is currently in Tesla's cars. This means that it is likely that the NMC811 will be introduced on the market, but we believe that the use of this battery in BEVs may take much more time. Part of Tesla's cost is that it had to build a pricey battery management system to keep an already expensive battery in check.

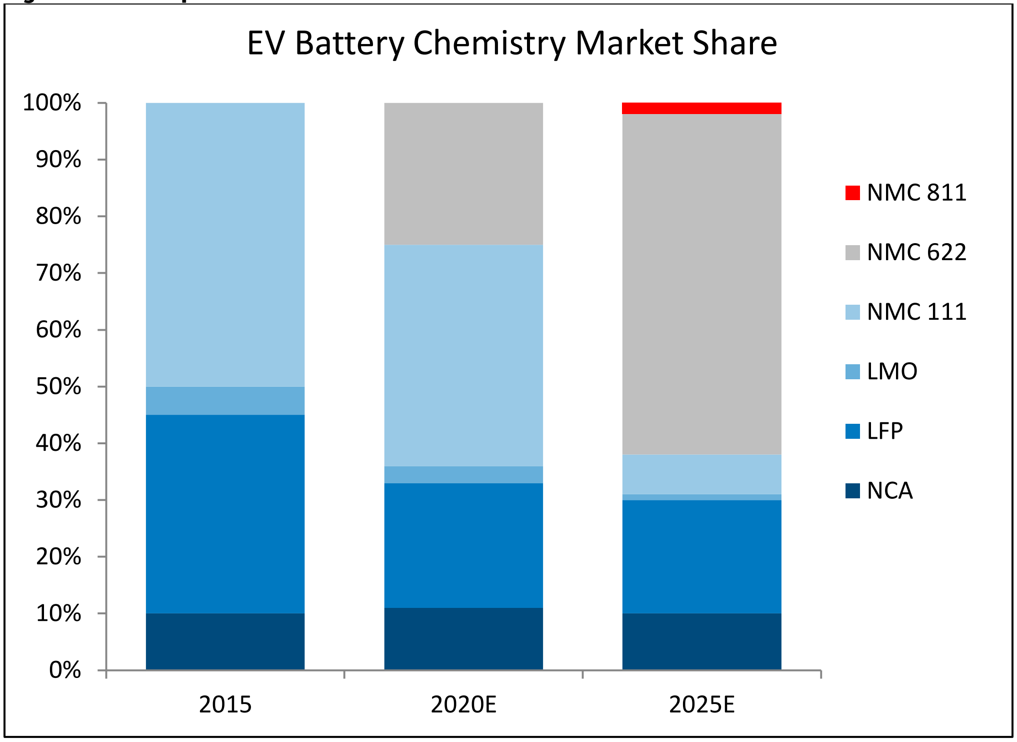
Given these insights we see three likely scenarios:

1. That a commercialized NMC811 battery will start to gain some market share from 2020 onwards.
2. The mass-produced NMC chemistries will be NMC622 or NMC442 due to technical issues we just described and the expense of the battery management system required to ensure safety and capacity retention.
3. The battery industry will continue to explore other cathode chemistries in an effort to reduce overall costs.

Therefore, **we assume a small market penetration of 4% of the NMC811 for 2025 in our models. For the time being,** we will maintain our NMC622 estimate of 60% penetration until we get a better sense of the expected roll-out of the NMC811 by LG Chem and SK Innovation in the next couple of years.

NMC chemistry has a complicated patent situation, which could lead to litigation and stall deployment

Figure 50: We Expect a Trend Toward More Nickel Content With ~20% Cobalt Content



Source: BMO Capital Markets

Battleground #2 → Improving the Battery Chemistry

The battery industry is touting NMC811 as the "next big thing" in this space, but we are cautious as this chemistry has safety risks and longevity issues that will not be easy to alleviate. Regardless, we are watching its evolution closely with intense scientific curiosity as battery heavyweights LG Chem and SK Innovations roll out their nickel-rich versions over the next couple of years.

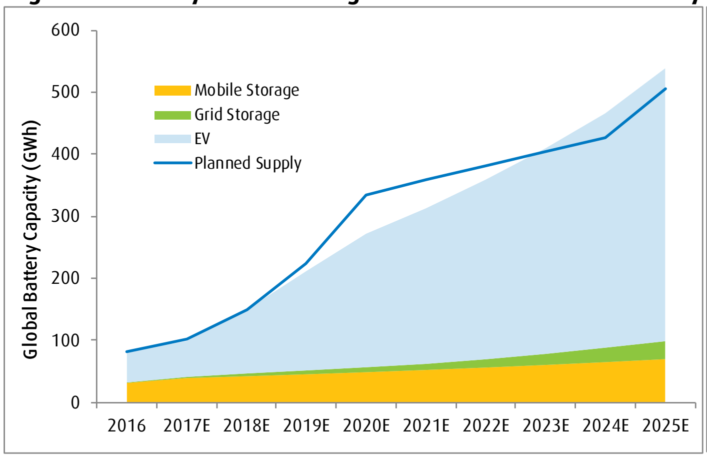
Litigation potential could stall NMC deployment. In addition to the technical difficulties, there are extensive patents surrounding the NMC chemistry that are related to modifications and manufacturing methods that are widely held among a variety of companies as well as various research labs. This labyrinth could set the tone for litigation that would stall its deployment. For example, BASF, Argonne National Laboratory and Umicore already have been embroiled in a complex patent dispute for a number of years, which was settled only in May 2017. With Umicore being a leading cathode supplier, this delay has been detrimental to NMC adoption.

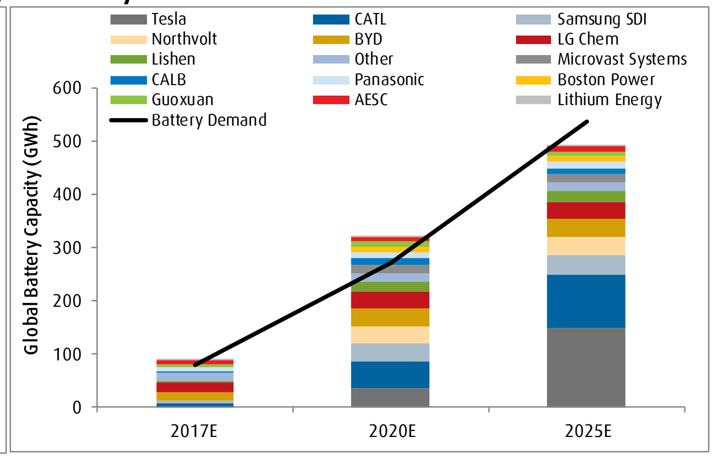
LIBs are the gold standard – but constraints exist. We also believe that in general, the lithium battery technology is currently the gold standard in this space and will likely continue to play a significant role as the energy and power storage revolution evolves. We see that the industry has set its sights on improving the internal chemistry as there are significant constraints in this space:

- **Intellectual and financial capital** – Battery manufacturers as well as upstream cathode, anode, separator and electrolyte suppliers have to contend with ramping up and maintaining both intellectual and financial capital to compete in this space.

- **Securing necessary materials** – Companies will also have to contend with securing the necessary raw materials at battery grade levels. By far, most investment is going to the cathode side with 22% of the cost and we are seeing a definitive trend of improving the NMC, LMO and LFP chemistries for EV applications.

Figure 51: Battery Producers Might Be Pressed to Handle Battery Demand by 2025





Battery demand refelcts capacity (GWh) needed to reach our base case estimates of EV, mobile, and grid storage.

We assume an 0.9kg/kWh conversion ratio for mobile and grid storage, and per vehicle battery capacity of 41kWh for BEVs, 10kWh for PHEVs, and 300kWh for E-buses respectively.

Source: VDMA, Company Data, BMO Capital Markets

The Lithium Ion Battery Landscape

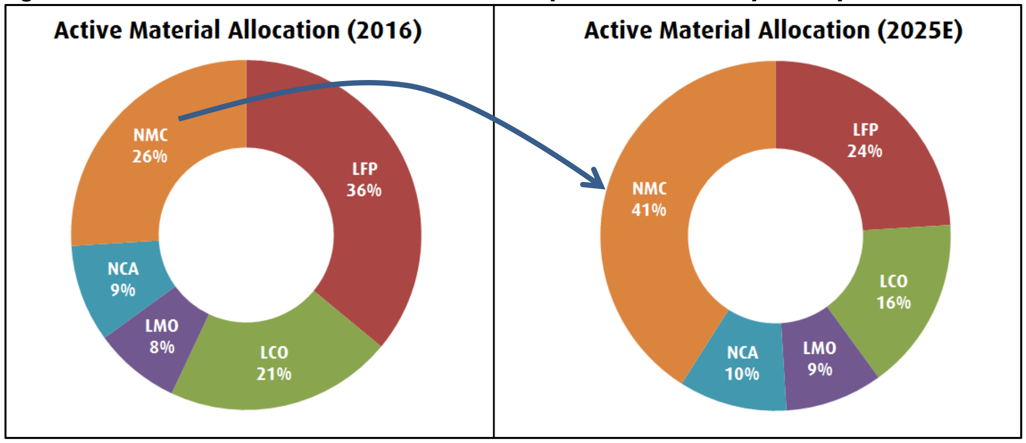
The top players in the lithium ion battery sector are currently LG Chem and BYD, with each having 16-17% market share. These companies are followed by CATL, Panasonic and AESC with 8% each. LG Chem and Panasonic (with its supply agreement with Tesla) are the leading battery suppliers for the North American market. LG Chem's battery technology is by far the most-used as it is used by Chevy, Ford and Nissan; LG Chem has also been working closely with Geely and Hyundai as well. Many OEMs, such as BYD, develop and manufacture lithium ion batteries internally.

Figure 52: LG Chem and Panasonic Already Have a Significant Lead in North America

EV	Battery Size (KW)	Cathode type[1]	Battery Manufacturer
BMW i3	33	NMC	Samsung/Bosch
Chevrolet Bolt	60	NMC	LG Chem
Fiat 500e	24	NMC	Samsung/Bosch
Ford Focus EV	34	NMC	LG Chem
Kia Soul EV	27	NMC	SK Innovation
Mercedes B250e	32	NCA(NMC)	Panasonic/SK Innovation[2]
Mitsubishi i-MiEV	16	LMO	Toshiba
Nissan Leaf (2018)	40	LMO/NMC	AESC/LG Chem
Tesla Model S, X	90	NCA	Panasonic/Tesla
Volkswagen e-Golf	36	NMC	Panasonic (Sanyo Div.)

1. All anodes used are graphite except the Mitsubishi I, which uses lithium titanium
2. Mercedes is in the process of changing their NMC supplier
Source: Blomgren, 2017

Figure 53: Cathode Active Materials Allocation Is Expected to Be Mostly NMC by 2025

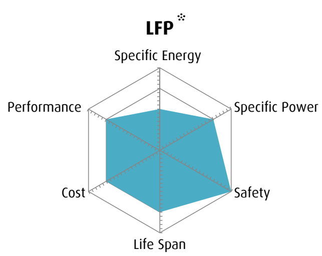


Source: Avicenne Energy

LFP Battery Will Still Have Significant Market Share in 2025

NMC (nickel, manganese, and cobalt) chemistry is expected to be the dominant cathode material –increasing to 41% in 2025

While we are mainly focusing on NMC battery chemistry in this report, we also believe that LFP (lithium iron phosphate) cathode will continue to be an important battery in the EV space. Used in China, the LFP battery is the cheapest (iron is ubiquitous) and the safest as it has very high thermal stability. However, the LFP battery has the lowest energy density of all the chemistries available. Therefore, it is slowly being phased out as the subsidies favour batteries with more energy density. This means that in order to increase energy density, more cells are required, making the vehicle heavy. Indeed, China's push toward using the NMC chemistry raises the question regarding cobalt supply. While some of the country's output comes from ore within its borders, most of its supply comes from partially refined cobalt imported from the Democratic Republic of the Congo (DRC). Therefore, the idea that LFP will be completely replaced is questionable and we believe that while LFP's market share will slowly drop, the battery will still be at a ~24% share in 2025.

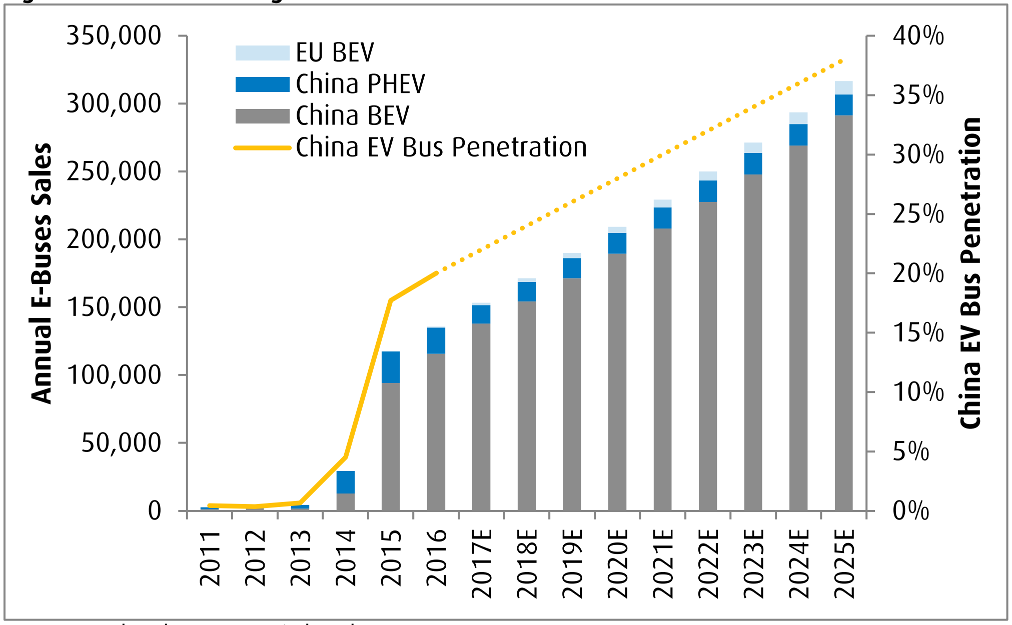


LFP (lithium iron phosphate) has low specific energy meaning more cells are needed to increase vehicle range

Part of LFP's longevity on the market will be in the electric bus (E-bus) market. E-buses are deemed by many as an ideal electric vehicle as they are large enough to house a very large battery (estimated ~300kWh average pack size) to get the necessary range. Furthermore, typical city buses have scheduled station stops that are in loops allowing for non-disruptive charging. China dominates the E-bus market with ~150,000 in sales in 2016, representing ~98% of global sales. E-Buses accounted for ~20% of all commercial bus sales in China in 2016, and we expect ~40% penetration by 2025. Europe and the U.S. largely remain in the demonstration phase, with only a few hundred sales across both markets in 2016. We expect the E-bus market to roughly double globally by 2025 as China's BYD Co. Ltd. continues to build manufacturing facilities around the world. BYD's buses are powered by a 324kWh LFP battery that can go 186 miles on a single charge.

*Source: Liu et. al., 2017, Battery University, BMO Capital Markets

Figure 54: China Is Driving Growth in the E-Bus Market



Source: EV Sales Blog, BMO Capital Markets

Figure 55: Lithium Ion Battery Companies Mostly Reside in China

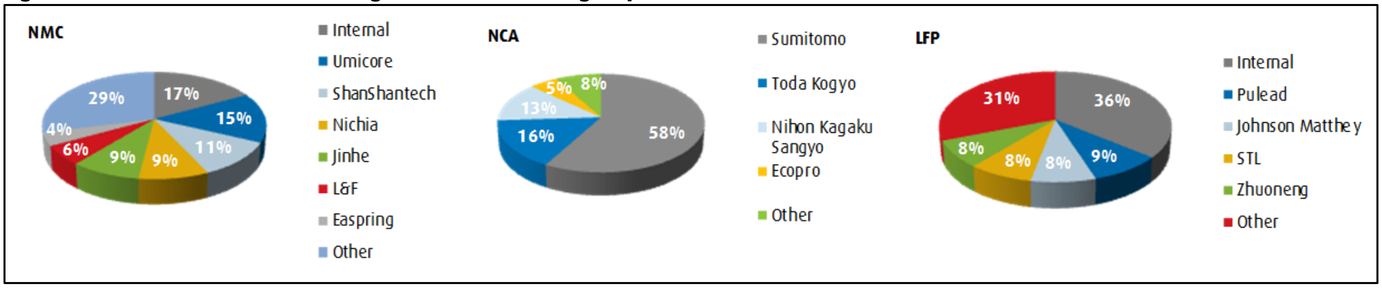
Battery Companies	Country of Origin	Exchange	Symbol	Main Attributes
BYD Co. Ltd.	China	SHE	2594	Produces mostly LFP for its own use
CBAK Energy Technology, Inc.	China	NASDAQ	CBAK	Mostly LFP
Chaowei Power Holdings Limited	China	HKG	951	Working with Exide to introduce Li-ion batteries in India
Coslight Group	China	HKG	1043	Leading lead battery supplier and LFP
Deutsche Accumotive GmbH & Co.	Germany	FWB	DAI	A subsidiary of Daimler AG
Electrovaya Inc.	Canada	TSX	EFL	Stationary power and forklifts
GS Yuasa Lithium Power	Japan	TYO	6674	Expanding range through a titanium anode
Guoxuan High-Tech Co., Ltd.	China	SHE	002074	LFP for JAC and Zoyte auto
Johnson Controls International Plc	Ireland	NYSE	JCI	Leader in lead acid batteries and lithium ion for PHEVs
Leclanché	Switzerland	SIX	LECN	Customizable solutions for the EV industry
LG Chem Ltd.	South Korea	KRX	51910	Expects to introduce NMC811 late 2018
Panasonic Corporation	Japan	TYO	6752	Mainly NCA batteries for Tesla
Samsung SDI Co. Ltd.	South Korea	KRX	6400	Unvelled its 2170 battery solid state battery
SK Innovation Co.	South Korea	KRX	96770	Expected to release NMC811 in late 2018
TDK Corporation	Japan	TYO	6762	Mainly LCO for Samsung and charging technology for Evs
Tianneng Power International Limited	China	HRG	819	Wide array of rechargeable batteries
Amperex Technology Limited (ATL)	China	Private		Main LCO supplier to Samsung
Automotive Energy Supply Corporation (AESC) [1]	China	Private		LMO-NMC mix
Beijing National Battery Technology	China	Private		Specializes in LFP
Beijing Pride Power Battery Technology Co. Ltd.	China	Private		LFP for BAIC
Boston Power Inc.	U.S.	Private		Manufacturing & R&D centre is in China
Cadenza Innovation Inc.	U.S.	Private		R&D stage company
China Aviation Lithium Battery Co., Ltd. (CALB)	China	Private		LFP batteries for Evs & locomotive
CITIC Guoan Group Co. Ltd.	China	Private		LMO-NMC mix
Contemporary Amperex Technology Co Ltd (CATL) [1]	China	Completing IPO		LFP for E-buses and BAIC; NMC for Geely
Dongguan YueDong New Energy Technology Co., Ltd	China	Private		Manufactures LFP for EV applications
Guizhou Anda Technology Energy Co., Ltd	China	Private		Specializes in LFP
Hitachi Vehicle Energy, Ltd.	China	Private		Lithium ion batteries for HEVs
Li-Tec Battery GmbH	Germany	Private		A subsidiary of Daimler AG
Lithium Energy Japan Corporation (LEJ)	Japan	Private		Merger between GS Yuasa's and Mitsubishi's battery division
Microvast, Inc.	China	Private		Lithium titanate in the anode
Northvolt AB	Sweden	Start-up		Teamed up with ABB to build a gigafactory for Europe
Romeo Systems, Inc.	U.S.	Private		Raised $30 Million in Seed Funding
SAFT Group SA	France	Private		Battery in many of France's EV brands
Shenzhen Bak Battery Co., Ltd.	China	Private		LFP; JV with Ayvip for E-buses
Shenzhen OptimumNano Energy Co., Ltd.	China	Private		Focused on EV and E-Bus LFP applications
Suzhou Phylion Battery Co., Ltd.	China	Private		Specializes in electric bikes and hybrids
TerraE-Holding GmbH	Germany	Private		Consortium of 17 companies and research institutions
Tianjin Lishen Battery JS Co., Ltd. (Lishen)	China	Private		LFP for Evs and E-buses
Valence Technology, Inc.	U.S.	Private		LFP for Evs and E-buses
Wanxiang Group	China	Private		A123 Systems and Fisker are subsidiaries
Zhuhai Yinlong New Energy Co., Ltd.	China	Private		LFP and E-buses

Source: Company reports; BMO Capital Markets

Market Share Will Change With the Next Big Improvement

We believe that the current market share will change with the next big improvement within the battery chemistry. Cathode companies are duking it out to improve existing chemistries (NMC, NCA and LFP), while others are trying to find new formulations altogether. While the business appears to be focused on the cathode, other improvements to the battery are also coming to fruition. For example, many companies are trying to create dendrite-proof separators or are looking to improve or replace the current electrolyte and the anode materials commonly used.

Figure 56: Market Share Will Change With the Next Big Improvement



Internal manufacturers include: BYD, Samsung SDI, Panasonic, Guoxuan, among others
Sumitomo dominates the NCA supplier market as they supply Panasonic/Tesla
Source: Avicenne Energy

Figure 57: Cathode Suppliers Are Duking It Out to Improve Existing Chemistries

Cathode Manufacturers	Country of Origin	Exchange	Symbol	Cathode Type
3M Company	**U.S.**	**NYSE**	**MMM**	**NMC**
BASF SE	**Germany**	**ETR**	**BAS**	**NMC**
Beijing Easpring Material Technology Co., Ltd	China	Private		LCO/NMC/NCA
Charge CCCV LLC	U.S.	Private		Next Generation
DuPont	**U.S.**	**NYSE**	**DD-B**	**NMC**
Ecopro Co., Ltd.	South Korea	Private		NCA
Foshan Zhaoneng Battery Industrial Co., Ltd.	China	Private		LCO
Henan Kelong New Energy Co., Ltd	China	Private		LNO (R&D)
Hunan Reshine New Material Co., Ltd	China	Private		LCO/NMC/LFP
Hunan Changyuan Lico Co., Ltd.	China	Private		LFP
Johnson Matthey	**U.K.**	**LON**	**JMT**	**LFP**
L&F Co., Ltd.	**South Korea**	**KRX**	**66970**	**LCO/NMC**
LG Chem Ltd.	**South Korea**	**KRX**	**51910**	**NMC/NCA**
Mitsui Chemicals Inc.	**Japan**	**TYO**	**4183**	**LFP**
Nichia Corporation	**Japan**	**TYO**	**5393**	**LCO/LMO/NMC/LFP**
Nihon Kagaku Sangyo Co., Ltd.	Japan	Private		NCA
Ningbo Jinhe New Materials Co., Ltd.	China	Private		LCO/NMC
Posco ESM	China	Private		NMC
Pulead Technology Industry Co., Ltd.	China	Private		LCO/NMC/LFP
Shanghai Shanshan Tech Co., Ltd.	China	Private		LCO/NMC/LFP
Sumitomo Corporation	**Japan**	**TYO**	**8053**	**NCA/NMC**
Tanaka Chemical Corp.	**Japan**	**TYO**	**4080**	**NMC**
Tianjin B&M Science and Technology JS Xo., Ltd.	China	Private		LFP
Tianjin STL Energy Technology Co., Ltd.	China	Private		LFP
Toda Kogyo Corp	**Japan**	**TYO**	**4100**	**NCA**
Umicore N.V.	**Belgium**	**EBR**	**UMI**	**LCO/NMC**
Very Small Particle Co., Ltd	Australia	Private		LFP
Xiamen Tungsten Co., Ltd. (XTC)	**China**	**SHA**	**600546**	**NMC**

Source: Company Reports, BMO Capital Markets

Figure 58: Companies That Improve the Anode, Electrolyte and Separator Will Also Win Big

Battery Material Suppliers	Country of Origin	Exchange	Symbol	Anode	Electrolyte	Seperator
Asahi Kasei Corporation	**Japan**	**TYO**	**3407**			
Amprius, Inc.	U.S.	Start-up				
BASF SE	**Germany**	**ETR**	**BAS**			
Bejing Institute of Chemical Reagents	China	Private				
BTR New Energy Materials Inc.	China	Private				
Cangzhou Mingzhu Plastic Co., Ltd.	**China**	**SZ**	**2108**			
Capchem Technology Co., Ltd. [1]	**China**	**SHE**	**300037**			
Celgard, LLC	U.S.	Private				
Dongguan Kaixen Battery Material Co., Ltd.	China	Private				
Enevate Corporation (raised $60 million)	U.S.	Start-up				
Formosa Energy & Matreial Technology Co., Ltd	China	Private				
Global Light Hi-Tech	China	Private				
Guotai-Huarong Chemical New Material Co., Ltd	China	Private				
Hitachi Chemical Company, Ltd.	**Japan**	**TYO**	**4217**			
Hollingsworth & Vose Company	U.S.	Private				
Hunan Shinzoom Technology Co., Ltd.	China	Private				
Liaoyuan Hongtu Seperator Technology Co., Ltd.	China	Private				
Ionic Materials, Inc. (raised $4.3 million)	U.S.	Start-up				
Jiangxi Zichen Technology Co., Ltd	China	Private				
Kunlunchem	China	Private				
Mitsubishi Chemical Corporation	**Japan**	**TYO**	**4188**			
Mitsui Chemicals Inc.	**Japan**	**TYO**	**4183**			
NEI Corporation	U.S.	Private				
Nexeon Ltd. (raised $108 million)	U.K.	Start-up				
Panax E-tec Co., Ltd	South Korea	Private				
Shenzhen Senior Technology Material Co., Ltd.	China	Private				
Shanghai Shanshan Tech Co., Ltd.	China	Private				
Shenzhen Sinuo Industrial Development Co., Ltd.	China	Private				
Smooth Way	China	Private				
SolidEnergy Systems (raised $20.5 million)	U.S.	Start-up				
Solvay [2]	**Belgium**	**ADR**	**SOLVY**			
Tanaka Chemicals Corp.	**Japan**	**TYO**	**4080**			
Targray Technology International Inc.	Canada	Private				
Tianjin Jinniu Power Sources Material Co., Ltd.	China	Private				
Tianjin DG Membrane Tech. Co., Ltd	China	Private				
Tinci Materials Technology Co., Ltd.	China	Private				
Toray Battery Separator Film Co., Ltd.	Japan	Private				
Toyama Chemical Co., Ltd.	**Japan**	**TYO**	**4901**			
Ube Industries, Ltd.	**Japan**	**TYO**	**4208**			
XianXiang Zhongke Science & Technology Co., Ltd	China	Private				

1. Capchem Technology has acquired BASF's Greater China's electrolyte business

2. In February 2017, Solvay acquired DuPont's Energain seperator and electrolyte formulations for an undisclosed amount.

Source: Company Reports, BMO Capital Markets

Part III – A (Very) Deep Dive on NMC Cathode Chemistry

Changing the internal chemistry is not easy. Whether it is changing the electrolyte, anode or the cathode, there are trade-offs between increasing energy density (increase vehicle range), cost and safety. The NMC cathode chemistry demonstrates this push and pull between capacity, safety and costs in a way that symbolizes the challenges the battery industry is facing and working hard to overcome. Essentially, the battery can't be easily "tweaked" and even increasing nickel content or decreasing cobalt below a given standard has consequences to safety and overall performance that cannot be alleviated.

Here, we are going to go into a very deep dive on the concepts introduced in the "Science Behind the Numbers" section and discuss how the individual elements of nickel, cobalt and manganese react on their own within the lithium ion battery and why they are combined in the NMC chemistry

Lithium-Ion Batteries – Current Gold Standard for BEVs

We see the lithium ion battery as the main power storage method for at least another five years

The lithium-ion battery (or LIB) is clearly the gold standard (for now) for power storage and has allowed mobility while staying connected to work, family, and communities. It has also been the technology of choice for car manufacturers to electrify their fleets and a key reason behind the electric car revival. In the 1990s, the famous documentary *"Who Killed the Electric Car"* debated why electric cars were not mainstream, citing everything from big oil bullies colluding with car manufacturers to a lack of government incentives to blaming customers for not demanding more environmentally responsible solutions. However, while these may or may not be valid points, the demise of the 1990s electric car revival can be mostly attributed to the battery technology at the time and the lack of a champion to invest in technological improvements.

Optimizations of cell design such as packing density and structure have plateaued

Growth of EV market has been driven by governmental regulations and incentives. As we discussed in the previous sections, the growth of the EV market over the past five-to-ten years has been driven by governmental regulations and incentives (e.g. tax breaks and rebates), a demand for vehicles that reduce local greenhouse gas (GHG) emissions, and the LIB technology in which the scientific community and gas car industry giants, such as GM and Ford, are investing heavily to improve. While there may be alternatives or newer technologies in the pipeline, for right now and at least for the next five years, the capital is invested here. It takes many years for a new technology to go from the R&D level to the commercial level. While it could be argued this process is becoming faster, the scientific literature started to conceptualize the lithium-ion battery in the late-1950s, the birth of the modern LIB was in the 1980s by the Goodenough lab of the University of Texas, and it was commercialized only in 1991 by Sony to make its electronics line more portable. We found peer-reviewed research regarding the use of LIBs to power electric vehicles as early as the 1970s.

Industry is heavily invested and is now focused on improving the internal components

Lithium ion battery likely to be main power storage method for next five years. We believe that despite the more rapid uptake in technology (steeper S-curves now compared to 50 years ago), we see LIBs as the main power storage method for at least another five-years. Even then, we believe there will be improvements and changes to the chemistry rather than a complete overhaul of the power sources in EVs especially given the costs of implementing charging infrastructures. The literature is clear that the techniques to optimize cell design, such as packing density and battery structure, have advanced to a point where there is little room for improvement. Therefore, the industry is largely focused on tweaking the electrochemistry by improving the cathodes, anodes, electrolyte and separators.

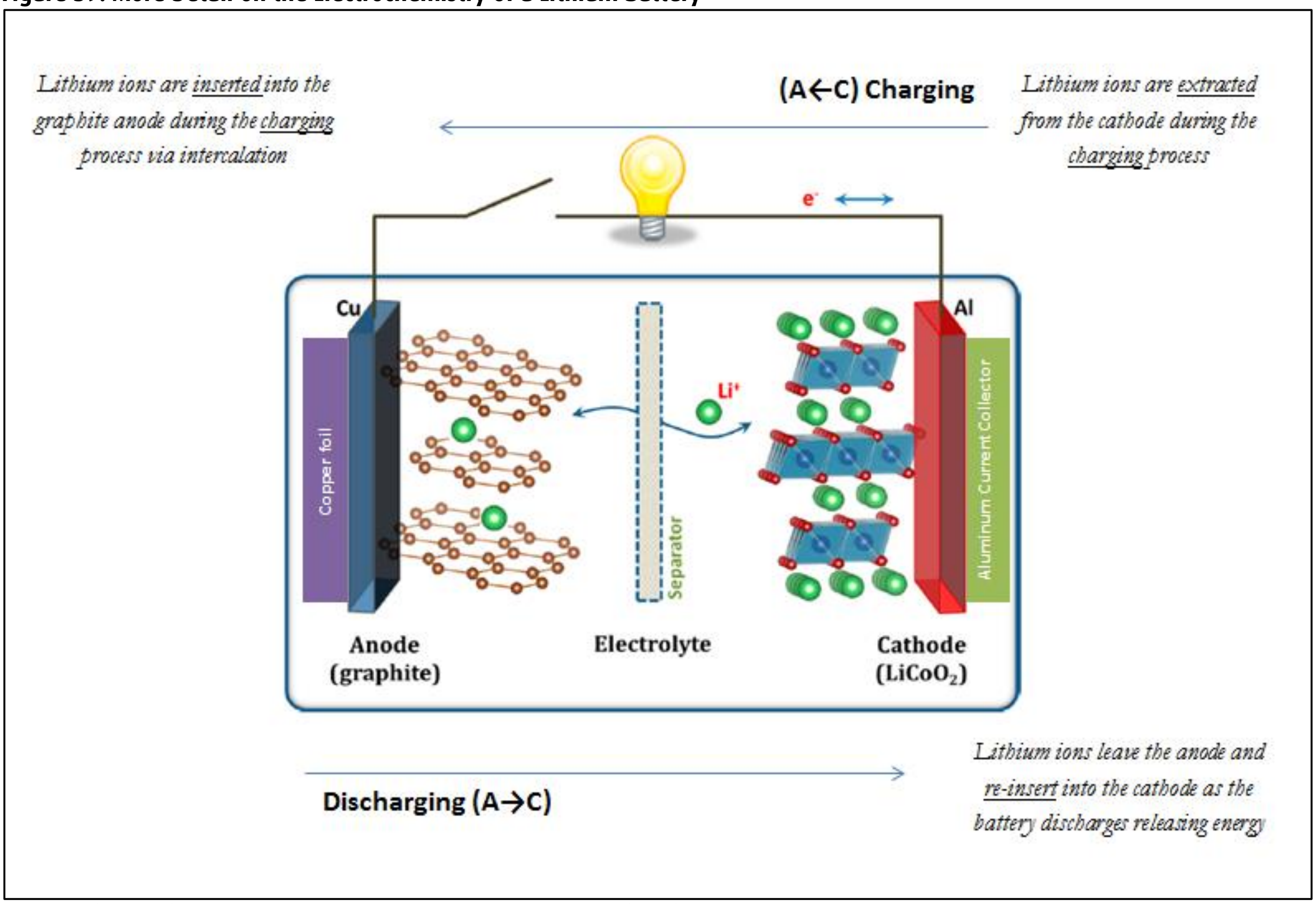
The Movement of Lithium Back and Forth Translates Into a Great Deal of Energy

Its high power comes from the ability of the cathode and the anode to accept and release the lithium ions

Lithium is a soft, easily oxidized alkali metal with properties that render it a good conductor of heat and electricity. The lithium ion battery is an umbrella term used to describe a number of different chemistries (LCO, LFP, LMO, NMC, NCA) where lithium ions move from the cathode to the anode when charging, and moves in the opposite direction when discharging. Once at the electrodes (cathode or the anode), lithium insert itself in a process called *intercalation*. While we will use this term sparingly, in corporate presentations scientists often state that the ions intercalate into the cathode. The main takeaway is that lithium has unique characteristics — **its easy movement back and forth translates into the ability to store large amounts of energy**. This process is sometimes referred to as a "rocking chair" mechanism.

Since battery performance is primarily a function of the ability of the cathode and anode to accept and release lithium ions, power and time between cycles are largely dependent on the chemical composition of the electrodes. Specifically, it is the ability of the materials that make up the electrode to react with other battery components and the available space within the structure to accept lithium ions that differentiates the uses of the common chemistries out there (LCO, LFP, LMO, NMC, and NCA). LCOs are typically used in mobile devices, while LFP, LMO, NMC, and NCA are the technologies of choice for car manufacturers as they electrify their fleets.

Figure 59: More Detail on the Electrochemistry of a Lithium Battery



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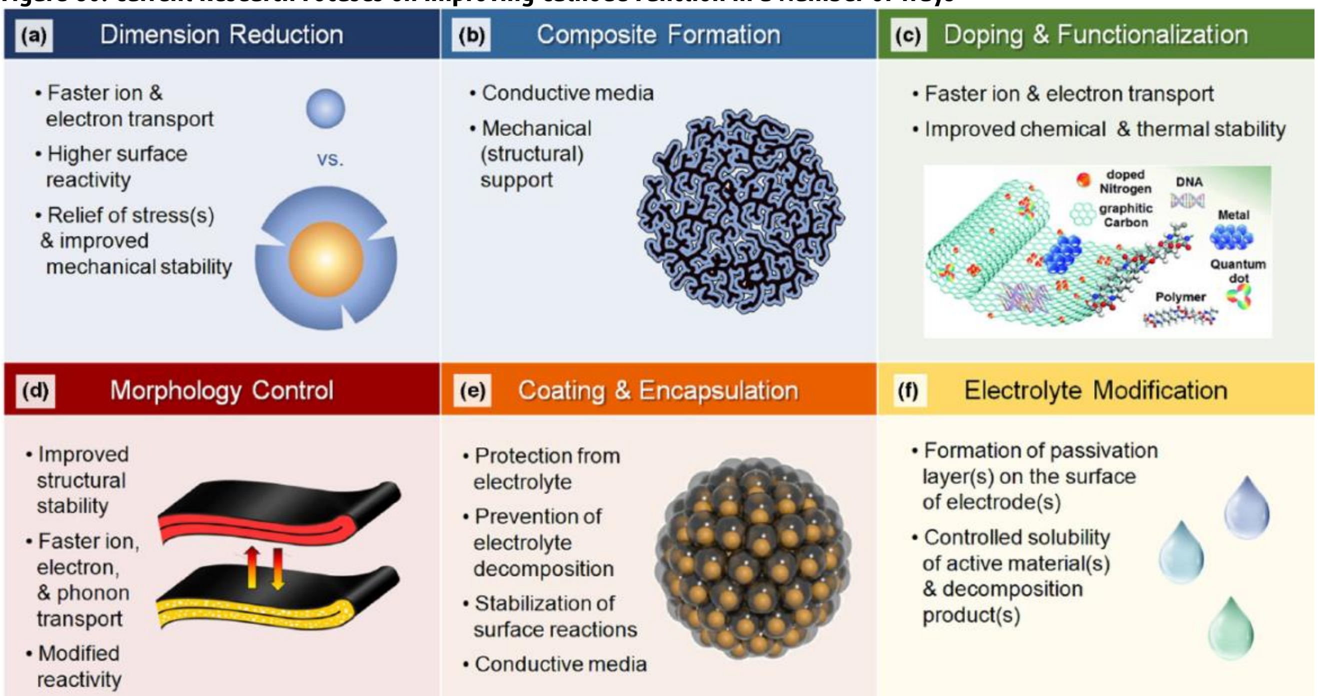
Since the cathode is the limiting factor of the entire system (and costly), improving its function is the current focus of the battery industry

Charging a battery or the ability of the battery to become 'charged' and ready for use, is directly related to the ability of the cathode to accept lithium ions into its structure. However, since the anode material (usually graphite) has higher storage capabilities, *the cathode material is the limiting factor of the entire system*, and enhancing this ability is the focal point of the industry and the scientific community. This certainly makes sense since the drawbacks of LIBS (costs, safety, low range and low temperature threshold) are largely predicated on the ability of the cathode to do its job. Currently, researchers are primarily looking at *ways for to improve cathode performance* that includes faster intercalation (dimension reduction), structural integrity (composite formation, doping, morphology control, and coatings), and modifying the electrolyte so it does not degrade and attack the active materials (Co, Mn, Ni and Fe).

Figure 60: Current Research Focuses on Improving Cathode Function in a Number of Ways



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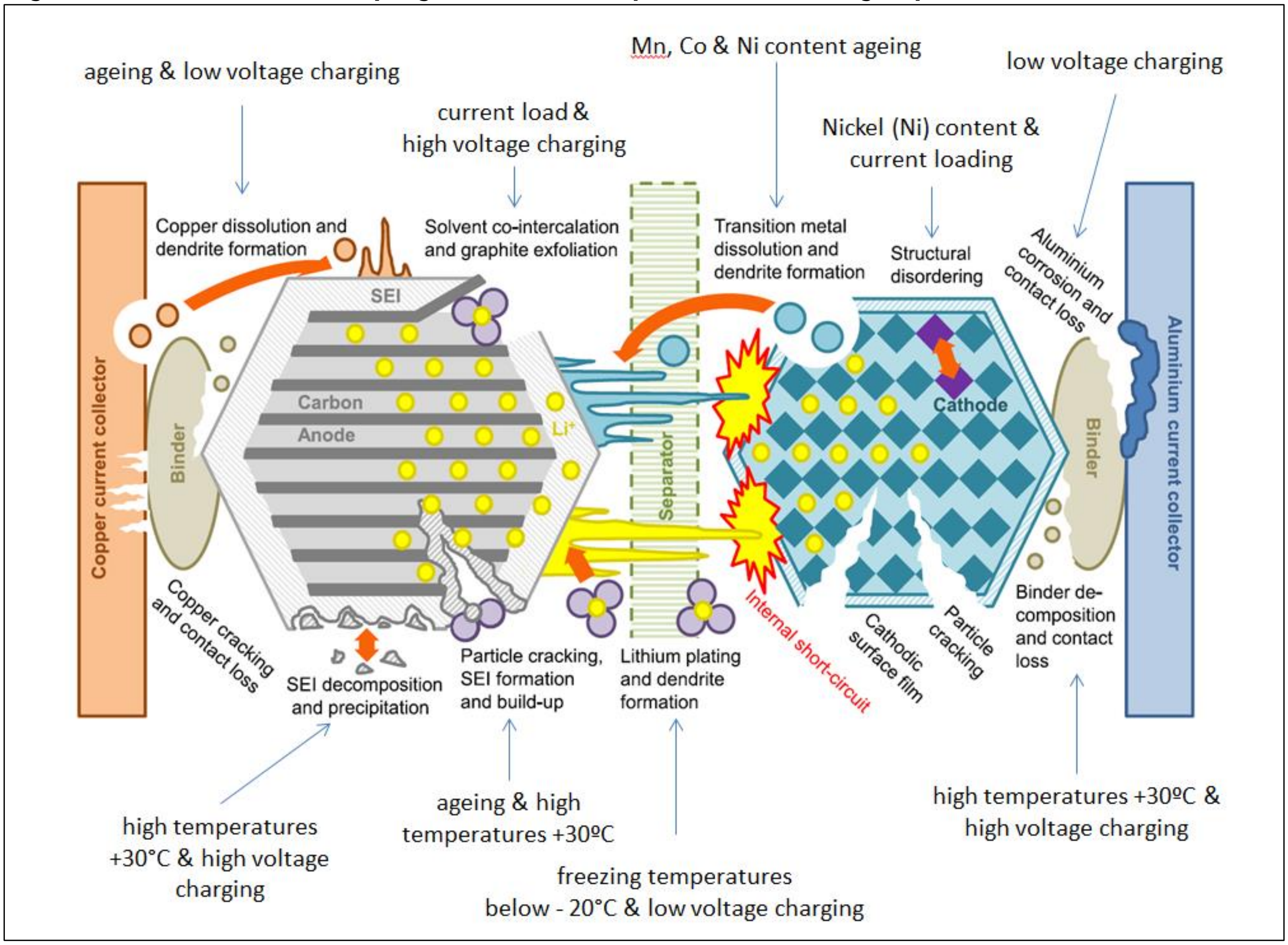
Complex Degradation Factors Reduce Longevity

Superchargers may be useful in a crunch, but continuous use shortens the lifespan of the battery

In general lithium ion batteries have finite lives and manufacturers often state how long these batteries are supposed to last, but there are a number of very complex degradation factors that can easily reduce that estimate. Figure 61 shows the number of physical and chemical processes that degrade the battery. Typically, the end-of-life (EOL) criterion for LIBs is 80% residual capacity from its pristine condition or a 30% increase in internal resistance. Manufacturers typically use the "state-of-health" or SOH metric to measure battery capacity; however, there are a number of ways to determine this. Defined as the discharge capacity of an aged cell compared to a new one, there are a number of algorithmic models programmed by various battery management systems, which differ among OEMs. However, the difference between the actual number of cycles and the estimates are due to parameters that cannot be readily determined or controlled. These are temperature, charging and driving behaviours.

Figure 61: A LOT CAN HAPPEN! Many Degradation Factors Impact Function and Longevity



Source: Birkl, C. *et al.* (2017). *Degradation diagnostics for lithium ion cells*. Journal of Power Sources; 341:373-386.

Changes to the LIB chemistry (even seemingly small ones) are not without consequences such as reduced safety and performance loss

The degradation mechanisms displayed above affect lithium-ion chemistries somewhat differently. For example, the manganese based LMO batteries are prone to degradation at high ambient temperatures and that damages the anode at a faster rate than other transition metals. But this does not mean that a heat wave won't affect other chemistries. Improvements in the chemistry tend to focus on suppressing these degradation factors in order to make it appealing from an economic perspective (↑EOL) and a safety perspective (lowering the chances of catching fire).

i. **Impractical optimal operation temperature range:** The battery is very sensitive to ambient temperature and the scientific consensus is that degradation processes begin outside of the 10°C-to-35°C range (50°F-to-95°F). This means that range becomes drastically reduced and the types of degradation mechanisms catalyzed reduce the life of the battery and can pose serious safety issues (e.g., thermal runaway). Although much of the earlier research focuses on the impact of heat waves, freezing temperatures are also a serious concern—specifically, that freezing temperatures increases the rate of lithium plating, which is the precursor to dendrite formation. Dendrites are a complex phenomenon that plagues the battery industry because its origins are largely unknown.

ii. **Charging is not as simple as 1-2-3:** Continually charging the battery to 100% and discharging to zero accelerates aging effects. Manufacturers often advise maintaining a partial charge of about 80-90% and not letting the battery discharge lower than 10%. Indeed, a high current load can damage the graphite anode and cause structural disordering in the cathode. Furthermore, superchargers may be useful in a crunch, but continuous use will shorten the lifespan of the battery, as this leads to contact loss, decomposition of the electrodes.

iii. **Calendar Aging:** Even if the battery is not being charged, parasitic side reactions within the battery cell lead to degradation of the battery. This includes transition metal dissolution (Ni, Mn, Co, Fe), structural disordering (Ni) and degradation of the electrolyte.

iv. **Degradation of the battery when not in use:** While self-discharge is much lower than in previous batteries, it is still an issue. Storing the car in a hot environment or at temperatures below freezing increase self-discharge rates.

There are trade-offs between the various battery chemistries and the perfect cathode does not exist

What this all means is that lithium-ion batteries are fussy. While the electrochemistry may seem like any other battery, it is much more volatile with a lot more going on. Changing the chemistry of any component (e.g. increasing nickel content in the cathode) can have consequences such as a reduction in safety and loss of performance. There are trade-offs between the various battery chemistries that we are now going to explore in greater detail. The LCO chemistry may have high specific energy, but it fails in specific power and safety. LFP and LTO batteries may be the safest, but LFP is low on specific energy.

The LCO (cobalt-only) and LMO (manganese-only) batteries are precursors to the NMC and NCA batteries. A nickel only cathode, called lithium nickel oxide or LNO, has not been commercialized for a number of reasons including that it is much more volatile than either the LCO or LMO batteries (at full charge). However, we looked into the extensive research on LNOs to get a sense of the ramifications in increasing the nickel content in the system. Therefore, we decided to look at how each element behaves in the system before talking about combinations such as NMC and NCA.

A Little More Detail for the Scientifically Inclined

The Reactivity of the Transition Metals Used in the Cathode

The different types of batteries are named after the chemistries of the cathode and typically use transition metals cobalt (Co), nickel (Ni), manganese (Mn) and Iron (Fe) as its principle raw material. Either alone or in combination, each has its share of advantages and disadvantages within the system. In other words, these elements have varying abilities to facilitate the shuttling of active lithium ions from the cathode and the anode or enhance cell capacity as performance is directly correlated with the amount of active lithium. Some can decompose and compete with lithium ions while others react with the electrolyte causing lithium loss. This is because they are transition metals with many oxidative states and readily transition from state to state ($Co^{2+} \leftrightarrow Co^{3+}$) meaning that reactivity is largely dependent on a particular state (Co^{2+} or Co^{3+}). Reactivity is very sensitive to the number of d-orbital electrons and crystal structure types. While we will be happy to go into more detail about the significance of this, we will instead simply state **that the reactivity of Ni^{3+} will be different from the reactivity of Co^{3+} or Mn^{3+} and will also be different than Ni^{2+} and Ni^{4+}.**

Sources: Doeff, 2013, Liu *et al.,* 2016

Figure 62: More Detailed Look at the Cathode Chemistries Discussed in This Section

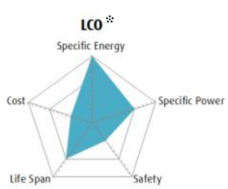
	LNO	LCO	LMO	NCA	NMC(111)[1]
Cathode Elements	Nickel	Manganese	Manganese	Nickel Cobalt Aluminum	Nickel Manganese Cobalt
Chemical Formula	$LiNiO_2$	$LiCoO_2$	$LiMnO_2$	$LiNiCoAlO_2$	$Li(NiMnCo)O_2$
Cost (per kWh)	-	$250-450[2]	$400-900	$600-$900	$500-$900
Self-Discharge		1-5%	5%	2-10%	1%
Specific Energy (Ah/kg)	150	150-200	100-150	200-260	NMC811:270 NMC622:225 NMC532:205 NMC111:199
Power Density Weight (W/kg) Volume (W/L)		600 1200-3000	1000 2000	1500-1900 4000-5000	500-3000 6500
Thermal Runaway (°C)		150 (Least Stable with a full charge promoting thermal runaway)	250 (Very Stable, but high charge promotes thermal runaway)	150 (Least Stable)	NMC111:305 NMC532:295 NMC622:265 NMC811:240
Safety	--	-	+	--	depends on nickel content
Potential vs Li/Li^+	3.8-4.2	3.45	4.1	3.8	3.7-4.0
Cell Voltage (V)	3.6	3.7-3.9	4.0	3.65	3.8-4.0
Charge Rate		0.8-1C	Up to 3C	0.7-4.2C	0.7C-1C
Cycle life[3] (lifespan)	-	500-1000 Depending on depth of discharge, load and temperature	300-700 (very low) Depends on depth of discharge and temperature	500-1000 Depending on depth of discharge, load and temperature	1000-2000 Depends on depth of discharge and temperature
Year Introduced	-	1991	1996	1999	2008
Main Application		**High Energy** Smartphones, laptops and cameras	**High Power** power tools, medical devices	**High Power and Energy** Medical devices, industrial applications, high end BEVs (Tesla)	**High Power and Energy** Current favorite as market share is rising

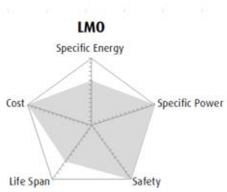
1. NMC cathode types vary by ratios of nickel(Ni), manganese(Mn) and cobalt (Co) content. For example, an NMC622 contains one atom formulated with 60%Ni, 20%Mn and 20% Co. In the industry and scientific literature NMC=NCM. The specific energy (capacity) increases with nickel content, however, the thermal stability decreases. A high charge promotes thermal runaway.
2. This is for a cellphone or tablet that does not need as much cobalt as would be needed in an EV.
3. Cycle life represents the number of complete charges a battery can perform until it reaches its end-of-life (EOL) of 80% its initial capacity or a 100% increase in the internal resistance.

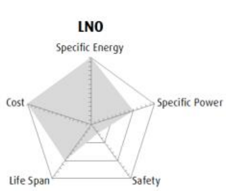
Sources: Battery University, Noh *et al.*, 2013, Julien *et al.*, 2014, Warner, 2015, Mauger and Julien, 2017, Liu *et al.*, 2017, BMO Capital Markets

1. LITHIUM COBALT OXIDE (LCO)

→ Why Can't It Be Used in EVs? – It's Too Explosive







Summary of Limiting Factors

- Higher financial and ethical costs because of the high concentration of cobalt — a rare, highly toxic metal that is principally mined in the DRC in abhorrent conditions.
- Extremely low safety profile and lower specific power eliminates its use in BEVs.
- Dangerous to charge at a rate higher than 0.8-1C due to the propensity to cause thermal runaway. It will actually explode within an hour using the superchargers commonly used in automotive applications.
- Has a concrete limit of 4.2V (upper cut-off voltage) for the reversibility of lithium ions meaning that overcharging leads to faster battery degradation and exothermic reactions that could lead to thermal runaway if battery management systems fail.

*Source: Liu et. al., 2017, Battery University, BMO Capital Markets

- Short lifespan limits its applications as stationary storage devices for the home and rural areas.
- LCOs require extensive battery management systems to regulate internal temperatures and prevent thermal runaway adding to an already expensive battery.

Discovered in the 1980s, the LCO battery is a layered structure that is the most used cathode chemistry in commercial batteries. A high volumetric capacity (1363mAh/cm^3), discharge potential (3.9-4.2V vs. lithium ions), discharge voltage and high theoretical specific capacity (274 Ah/kg) along with low self-discharge and great charging and discharging cycles have made it the battery of choice for smartphones, tablets and laptops. It is also *easy to produce without structural defects* as there is a notable size difference between lithium ions (0.76Å) and cobalt ions (0.545Å) compared to the nickel-rich cathodes we will be discussing later. However, there are a number of issues with LCOs that limits its use in large scale applications such as EVs and PHEVs.

Most thermally unstable cathode on the market under stressful and suboptimal conditions

The high cobalt concentration is the main reason why LCO batteries perform the way they do, as cobalt determines the specific energy or the amount of lithium that can be stored within the cathode. However, cobalt's performance is within very finite parameters as it can become very unstable in overcharge and high charge situations. In reality, the LCO cathode is the *most thermally and chemically unstable commercial cathode* under stressful or suboptimal conditions. The LCO battery with a thermal runaway temperature of 150°C has lower thermal stability than its peers because it becomes unstable in more abusive conditions.

Specifically, the *eagerness of cobalt oxides to release oxygen in high temperatures* and violently react with the electrolyte has pretty much eliminated its application in the transport sector especially after the Boeing 787 Dreamliner incident and subsequent grounding of the entire fleet. Thermal instability has also led to the widespread recall of many electronic devices and costly PR nightmares. For example, earlier this year, Samsung announced that its Galaxy Note 7 smartphone kept exploding because there *was not enough room between the heat protective seal and the electrolyte*. In other words, managing the reactivity of cobalt within the system is very difficult. This is why *smart luggage with non-removable batteries* has been banned from most airlines as checked baggage because they can be combustible in the lower storage compartments. That being said, LCO batteries are the most researched and developed chemistries on the market and researchers use LCOs as a reference point to compare other cathode materials in the scientific literature and we will do the same.

i. A Common Abuse – The Problems That Arise From Overcharging

Overcharging is a misnomer as the main culprit is heat

LCOs may have a high theoretical capacity of 274 Ah/kg which is why it was developed in the first place, but has a practical capacity of only 135-140mAh/g. This is because cycling is limited because charging capacity (lithium ions move cathode → anode) needs to be 50% of discharged capacity (lithium ions move anode → cathode). What this means is that LCOs do not perform well in overcharging (keeping the battery plugged in after reaching 100% capacity) or deep discharging (allowing the battery to completely discharge) scenario. It is interesting to note that the LCO chemistry is the most stable when cycled within this pretty tight range; however, it quickly becomes the least stable outside of those parameters. This is why researchers often say that the LCO battery has both the best and the worst cycling performance compared to its peers. As an aside, the word "overcharging" is somewhat of a misnomer here, as the LIB cannot really accept more charge than its capacity. The main culprit is in fact heat. As the charge reaches its threshold capacity (4.2V-to-4.5V), the current changes from an ionic transfer of lithium guest ions from the cathode to the anode (what we want) to an ohmic one causing resistance in the battery (i.e. loss of the I2R current), which in turn, generates a substantial amount of heat (what we don't want), and damages the battery.

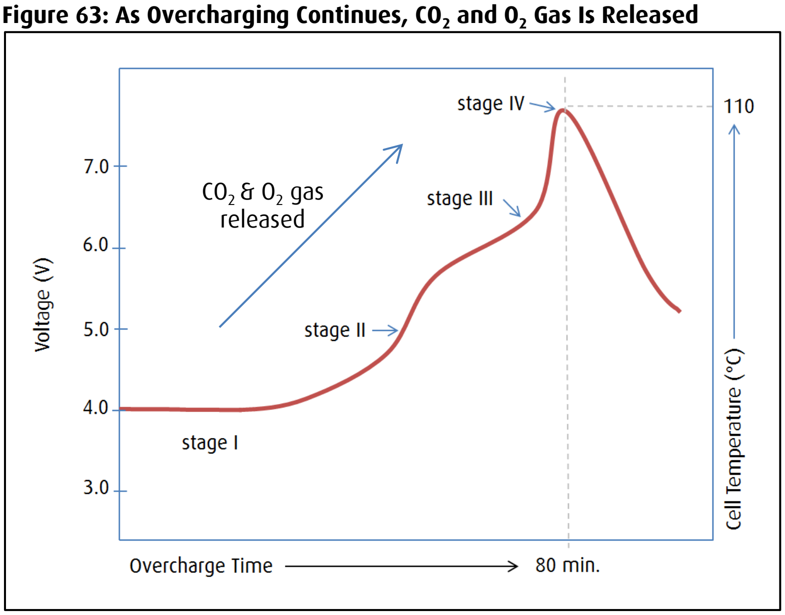
A Little More Detail for the Scientifically Inclined

LCOs Sensitivity to Overcharging Leads to Capacity Fade

The LCO battery has a rigid potential versus lithium ions of 4.2V. Researchers conducted overcharge tests of a 1000mAh LCO pouch cell and found that once the charge nears or passes the 100% mark, the current becomes forced and pushes the voltage past that 4.2V discharge potential. At this point, the battery loses capacity more rapidly than what would be deemed normal ageing. Another research group actually found that there was a severe drop in capacity at the 4.5V level at even a tenth of the normal charge (C/10). This means that the LCO chemistry is <u>sensitive</u> to overcharging, which if continued, leads to irreversible damage and, potentially, thermal runaway. This is the reason why smartphones that are continually charged overnight (i.e., remain plugged in after reaching 100% charge) noticeably lose capacity faster than those that are not charged overnight. Increasing temperatures within the cell causes the release of Li+ ions from the cathode and the formation Co^{4+} and oxygen gas. The release of these ions along with oxygen causes the loss of active materials and disruptive reactions with the anode and electrolyte, which damages the battery.

Sources: Amatucci *et al.* 1996; Oshaki *et al.,* 2005, Doh *et al.*, 2008

Figure 63: As Overcharging Continues, CO_2 and O_2 Gas Is Released



Source: Oshaki *et al.,* 2005, BMO Capital Markets

The loss of active cathode materials means the ability to shuttle lithium ions back and forth is also lost

Figure 64: The Stages That Lead to Thermal Runaway

Stage I	Lithium ions in the cathode irreversibly releases into the electrolyte once the cell starts being overcharged and deposits on the graphite anode. This causes a loss of overall lithium inventory that is available for normal operation of the cell.
Stage II	The loss of active lithium causes an increase in cathode resistance and the temperature increases. The rate of lithium starts to increase and the electrolyte also starts to decompose. As the situation continues, the reactivity of the electrolyte increases and the irreversible or lithium ions migrates and starts to react with the anode.
Stage III	As the internal cell temperature moves past 60ºC, CO_2 gas is formed from the reactions within the degrading electrolyte.
Stage IV	The introduction of oxygen into the system will lead to side reactions with the electrolyte and the anode in ways that if prolonged, can cause short circuits. At this point, the cell's internal temperature reaches the shutdown temperature of the separator (130-135°C) and the battery management systems force the entire system to shut down.

Sources: Oshaki *et al.,* 2005; Doh *et al.,* 2008; Belov and Yang, 2008

A Little More Detail for the Scientifically Inclined

The Chain Reaction as the Active Material Degrades

As the cathode loses more lithium (stage II and III) and the electrolyte becomes more reactive, the cathode itself decomposes in a number of ways. Co^{3+} oxidizes into the more unstable Co^{4+} that dissolves into the electrolyte leading to functional cobalt loss. Since the layered structure of the cathode is stabilized using CoO_2 sheets that are separated by octahedral coordinated lithium ions, it is susceptible to Jahn Teller distortions and the hexagonal crystal structure expands, resulting in a number of structural instabilities, causing the *release of more irreversible lithium and Co^{4+} into the electrolyte*. It also seems to form Co_3O_4 and oxygen. This is because the electron loss when going from Co^{3+} ($3d^6$ configuration) to Co^{4+} ($3d^5$ configuration) leads to the easy mixing of the cobalt and the oxygen atomic orbitals (i.e. hybridization of the $Co^{4+/3+}$:t_{2g} orbital with the O:2_p orbital) causing the *release of oxygen gas,* which in turn, *generates heat*. In other words, going from Co^{3+} to Co^{4+} releases oxygen, reacts with the electrolyte and increases the internal temperature.

Sources: Amatucci *et al.* 1996; Doh *et al.*, 2008, Julien *et al.,* 2014

Ultimately, the battery is typically shut down when the separator reaches its threshold temperature by the battery management system (BMS). But other than a loss of lithium inventory, why is there is such a noticeable capacity loss? As more and more cobalt ions and lithium ions that were supposed to be in the cathode leach into the electrolyte, the composition of the cathode also changes (i.e., changing from lithium cobalt (III) oxide to cobalt (II) oxide) meaning that there is a *loss of active cathode materials to shuttle the lithium ions back to the anode*.

ii. Charging an LCO Battery at >1.5C Increases the Likelihood of Explosion

If used in automotive applications, charging would be strictly limited to 1C

Typically, BEV chargers are classified as slow (1C), Medium (2C) and fast (3C). To put this in perspective, a 0.05C charge is required for a lead acid battery and the current rate of a cellphone charger is around 0.5C-to-0.8C. The higher charge current causes the reactions described earlier to happen at an increased rate. These reactions coupled with an overcharged anode cause violent reactions within the system. Charging with a 3C Tesla supercharger has been shown to cause the battery to catch fire or explode in less than an hour. Even at a charge rate of 2C, researchers found that the cell did not shut down when the separator temperature reached the critical point. Therefore, if used in automotive applications, ***charging would be strictly limited to 1C*** meaning that charging will take an unreasonably long time.

A Little More Detail for the Scientifically Inclined

Overcharging and Higher Charge Current Increase Dendrites Formation

If there is an excess amount of lithium ions in the electrolyte waiting to be accepted into the anode, it turns into metallic lithium and forms a hard surface coating on the anode (i.e., lithium plating). Lithium plating is the precursor to dendrite formation — a dangerous mechanism whose growth pierces the separator, causes short-circuits and causes an explosion when the dendrites reach the cathode. The reactions within the LCO allow both lithium and cobalt ions to plate the anode causing the plating to be much more severe. This means that the system has to rely on battery management systems to know when to shut down the battery. Typically, this happens when the separator reaches a critical temperature. However, many studies have concluded that irreversible damage occurs at 150% overcharge regardless of whether the separator shuts down or not. In the case of a charging rate of greater than 2C, the separator simply melted, unleashing thermal runaway reactions, which resulted in an explosion.

Sources: Oshaki *et al.,* 2005, Belov and Yang, 2008, Bugga and Smart, 2010

The LCO Chemistry Will Not Be Used in BEVs Anytime Soon

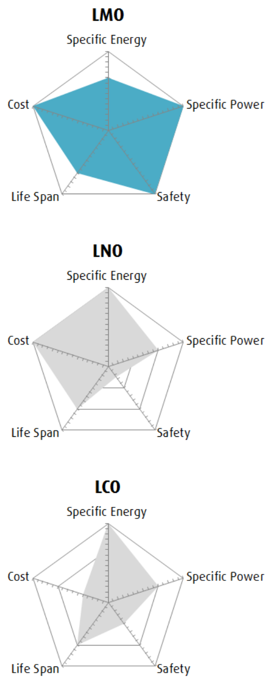
To use LCOs in EVs, the battery management system would have to be overbuilt, increasing cost and weight by 75%

After almost three decades of research, it appears that there is little that can be done given the reactivity of cobalt at such high concentrations. Therefore, we can conclude that the use of LCO LIBs in electric vehicles and large power devices *cannot occur without overbuilding battery management systems that can regulate currents and temperatures*. According to research from the Georgia Institute of Technology, this would increase the cost and weight by about 75%. Yet the battery is already expensive. From a pure materials standpoint, the already high costs of cobalt (5x the price of manganese) multiplied by the need for 10kg of cobalt for a single EV battery (1,000 times more than an iPhone) is not economically feasible. Furthermore, the human rights violations associated with cobalt mining in the Democratic Republic of the Congo (DRC), not to mention the environmental toxicity, have contributed to the recent push to either find ethically-sourced cobalt or replace it altogether.

There have been numerous attempts to find another transition metal that can be used in lieu of cobalt. For example, iron (Fe) and nickel (Ni) increases structural disordering within the cathode adding another technical hurdle to the mix. There was also much excitement over the substitution of cobalt (Co) with manganese (Mn) about 20 years ago. Indeed the LMO battery is being used on the market in a variety of first generation BEVs. However, it showed the same 50% constraint in cycling as LCOs, and lifespan, despite being safer with higher specific power.

2. LITHIUM MANGANESE OXIDE (LMO)

→ Low Capacity and Impractical in High Temperature Regions



Summary of limiting factors:

- The solubility of manganese in the second oxidative state (Mn^{2+}) limits the capacity, performance and the life span of the battery compared to other chemistries.
- Degrades quickly at elevated temperatures (e.g. heat waves) as heat accelerates typical aging mechanisms such as degradation of the electrodes and lithium loss.
- Has a rapid self-discharge rate that could leave people stranded
- The ease of transition between manganese states ($Mn^{2+} \leftrightarrow Mn^{3+} \leftrightarrow Mn^{4+}$) constrains charging to the 1.0-1.5C.

The LMO battery was discovered from efforts to remove cobalt from the equation and all its complications from both the technical complications we just described and the supply side implications that will be described in the last section of this report. LMOs are moderately safe (reactions do release some oxygen), have reasonably high specific powers (1000W/kg) and are lower cost due to the lack of cobalt and non-limiting supply of manganese. **These are the reasons why it has been the chemistry of choice for more reasonably priced BEV models at the early stages of the EV revolution.** Manganese is also environmentally benign and has limited biological consequences relative to cobalt or nickel. Indeed, at first glance, it had a lot of potential.

Despite these advantages however, LMOs have been phased out or blended with other chemistries as they have *decreased capacity that seems to decay more rapidly beyond ambient conditions*. The structure of the LMO cathode makes it particularly susceptible to side reactions, especially acidic ones, and it appears to decompose at much higher rates during cycling resulting in increased resistance within the battery. This means that its longevity is far shorter than its peers because of its chemical and physical make-up.

Scientists from the IMS Laboratories compared the four leading lithium-ion chemistries in EVs today, and found that LMOs have about one-fifth the longevity of its peers. In this experiment, end of life occurred in 105 days versus 452days for NMC, 749 days for NCA and 545 days for LFP. Furthermore, the use of manganese appears to affect the NMC chemistry as well as its closest rival, the NCA, has ~66% more life. We also believe that manufacturer battery replacement estimates cannot be trusted, as rates of degradation depend on a number of uncontrolled variables such as charging behaviours and ambient temperatures.

Source: Liu et. al., 2017, Battery University, BMO Capital Markets

A Little More Detail for the Scientifically Inclined

Leached Mn ions Wreak Havoc on the System and Reduces Structural Integrity

The leading theory to explain capacity loss is the *disproportionation* of Mn^{3+} on the cathode surface into Mn^{2+} and Mn^{4+} in the presence of the most commonly employed electrolyte $LiPF_6$). This redox reaction converts a transition metal into two different oxidation states. In this case, the reaction is $2Mn^{3+}_{(solid)} \rightarrow Mn^{2+}_{(solution)} + Mn^{4+}_{(solid)}$. It is believed that Mn^{2+}, the usual form of soluble manganese, leaches and dissolves into the electrolyte while Mn^{4+}remains on the cathode. This side reaction at the cathode is widely believed ***to cause about 23% of the overall capacity loss*** and jumps to 34% when temperatures rise to over 50ºC. Heat decomposes the popular $LiPF_6$-based carbonate electrolytes into hydrofluoric acid (HF), which then attacks the cathode increasing the rate of reduction of Mn^{3+} to Mn^{2+}.

Sources: Doeff, 2013, Julien *et al.,* 2014, Xu, *et al.*, 2015, Benedek, 2017

i. Side Reactions Involving Manganese (Mn) Cause Capacity to Fade

Manganese ions break away from the cathode, which causes a number of problems at the anode

Research to explain the lower-than-normal capacity and rapid decay point to the many side reactions involving the different manganese ions that tends to convert easily among each other ($Mn^{2+} \leftrightarrow Mn^{3+} \leftrightarrow Mn^{4+}$). Specifically that one of the manganese ions (Mn^{2+}) appears to emanate from reactions at the cathode very easily, dissolve in the electrolyte, *migrate into places where it should not go* and *competes with lithium ions* for space in the anode.

ii. Properties of LMOs Cause Structural Distortions Decreasing Capacity

The LMO cathode experiences structural changes when fully discharged as it loses its active material from side reactions ultimately leading to capacity loss at an increasing rate. Since charging and discharging of lithium ion batteries greatly depend on the structural integrity of the electrodes, this stress means that LMOs cannot be supercharged as well as other battery chemistries.

A Little More Detail for the Scientifically Inclined

LMOs are constrained by chemical and physical parameters that reduce range and increase charging times

Structural Distortions Limit the Charging Capabilities to 1-1.5C

Mn^{3+} in the cathode experiences phase changes at the end of discharge and is prone to irreversible structural distortions (called the Jahn-Teller effect). Ultimately, this leads to a phase change from a layered to a spinel material leading to capacity loss. This stress means that LMOs can only be charged at lower rates (1-1.5C) compared to others. Furthermore, the state of Mn^{3+} (d^4 cubic symmetry) can transform into a more unstructured state (tetragonal phase) during charging and discharging limiting lithium insertion to one Li per Mn and extraction to 0.8Li per formula unit and not one to one. Therefore, similar to LCO, cycling is limited to a strict domain (i.e. λ-MnO_2-$LiMn_2O_4$) meaning that the specific capacity is also much lower than other chemistries that do not have these constraints. In other words, *the range is considerably reduced* as the time between charges will be shorter and the length of time required to charge will be much higher than other BEV batteries.

Sources: Julien *et al.,* 2014; Xu *et al.,* 2015, Mauger and Julien, 2017

iii. Sensitive to High Temperatures

The rates of the side reactions caused by manganese increase as ambient temperatures rise (>45ºC), especially at full charge. The impact of high temperatures quickly became apparent in 2012 when Nissan had to recall many of its BEVs to replace the batteries because of severe capacity loss after a very hot summer. Generally, any cathode containing manganese will be very sensitive to high temperatures especially at full charge.

Scientists from the IMS in France have shown that any cathode containing manganese is problematic. Specifically that an NMC chemistry that contains ~33% manganese has issues with temperature as the degradation starts to amplify at 45°C compared to 60°C for the NCA battery that does not contain manganese.

A Little More Detail for the Scientifically Inclined

Disproportionation Reactions Destabilizes the Battery

Research shows that Mn^{2+} from the disproportionation reaction ($2Mn^{3+}_{(solid)} \rightarrow Mn^{2+}_{(solution)} + Mn^{4+}_{(solid)}$) does not completely dissolve in the electrolyte and some migrate to the anode end of the battery. Once there, it reacts with the anode in three possible ways. First, Mn^{2+} induces the thickening of the surrounding film, trapping the Li^{+} ions thereby reducing available inventory for charging and discharging purposes. A second possibility is that Mn^{2+} alters the Li ion transport by either reducing the permeability of the anode surface or drives them to the more non-productive edges of the anode. Third, Mn^{2+} deposits onto the surface of the anode and reduces to metallic Mn that to inhibit the intercalation of lithium into the anode. Furthermore, metallic Mn catalyzes reactions between graphite and the electrolyte that ultimately removes lithium ions from normal cell operation. As deposits or plating becomes more pronounced, internal resistance (iR2 current) increases causing instability.

There has been some recent research that counters the overall importance of this reaction in fading capacity. Namely work by Banerjee *et al.* 2017 found that $Mn^{3+}$is the main soluble species in the electrolyte solution and not Mn^{2+} suggesting that perhaps the redox reaction is not as big of an issue as previously thought. However, this insight is difficult to reconcile given what we know about the behaviours of Mn^{2+} and Mn^{3+} in aqueous solutions. Regardless, most research suggests that the loss of functional Mn^{3+} through the disproportionation reaction is the precursor to a chain of events that causes degradation of the electrodes, lithium inventory loss and increased resistance within the cell. What exactly happens may be open for discussion, but it does not matter. The capacity loss has yet to be remedied and LMOs are now blended with other chemistries to prevent this from happening.

Sources: Nitta *et al.,* 2015, Visser *et al.,* 2016, Banerjee *et al.,* 2017

Tried and Tested Solutions That Have Not Improved LMOs

LMOs have a lot of positive characteristics, but from the discussion above, we can see the reason why researchers are looking to improve the chemistry. Since the creation of Mn^{2+} from the disproportionation reaction is considered to be the precursor to capacity fade mechanisms, finding ways to stop this reaction remains a high priority. There have been a few practical solutions to resolve these issues such as coating the cathode, changing or modifying the electrolyte.

i. The Use of Coatings to Prevent Cathode Corrosion

Thin layers of Al_2O_3, zirconia, MgO, Li_2O-B_2O_3 glass, AlF_3 etc. can create protective barriers between the cathode and the electrolyte. However, while these coatings may provide the desired thermal stability, the recommended charging rates are still at 1C or below.

ii. Changing or Optimizing the Electrolyte

Changing the electrolyte from the popular lithium salt, $LiPF_6$, to an electrolyte that does not promote Mn^{3+} dissolution is another possible solution. In general, there is poor compatibility between LMOs and carbonate-based electrolytes such as this because $LiPF_6$ can decompose into hydrofluoric acid (HF), which subsequently initiates an acidic attack on the cathode. However, changing any part of the battery chemistry is extremely difficult. For example, the use of the LiTDI electrolyte may be more stable when it comes to the cathode materials, but it causes side reactions that degrade the anode that will also cause the capacity to fade. Therefore, the continued use of $LiPF_6$ in LIB chemistry is pretty likely in the next five years, especially given the drive to improve cathode chemistries. For now, there has been a tremendous amount of research focused on developing additives to stabilize the $LiPF_6$ and eliminate or inhibit HF formation.

A Little More Detail for the Scientifically Inclined

The Formation of Hydrofluoric Acid Increases the Formation of Mn^{2+}

The formation of HF in the two reactions above essentially accelerates the disproportionation of Mn^{3+}. Manganese is also thermally unstable and the electrolyte increases the rate of Mn^{2+} formation *as more HF is formed to strengthen the acid attack*. Proposed additives to stabilize the electrolyte include introducing a mild Lewis base that can form a complex with the PF_5. This would limit the amount of HF that can be formed. Others include thermal stabilizers, such as TTFP or 3% DMAc, that have been shown to provide better storage performance, higher capacity retention and cycling efficiency at elevated temperatures. There are also additives that could remove the acid from the system. For example, HMDS has been shown to reduce capacity fade by neutralizing the HF acid and removing water.

Sources: Julien *et al.,* 2014, Xu *et al.,* 2015

iii. Doping the LMO Cathode to Stabilize Manganese

Another solution has been to choose a cathode composition where Mn^{4+} remains inactive and does not reduce to the Mn^{3+} form. Doping is a solution to a number of the problems with cathode chemistry, but it is a bit of a 'dark art' so to speak. The technique has been extensively tested in an effort to improve LMOs and the LMO-blend with NMC chemistry has been the choice to replace first generation BEV batteries. There are a couple of doping methods that have been employed so far.

Doping the LMO cathode with NMC chemistry removes the destabilization factor but does not improve capacity

1. Doping the LMO cathode with NMC Chemistry is believed to be the best way to achieve a more balanced performance. Researchers found that the LMO-NMC cathode had the same issues as the LMO cathode alone except that the destabilization of the cathode and interference of manganese with the anode *occurred much later in the cell's life* making this degradation factor negligible. This means that the reactions that causes capacity fade would happen as the battery would be reaching its EOL anyway. This was the strategy employed by LG Chem for BMW in its first-generation models. However, introducing NMC

chemistry in this manner reduces its safety profile and still does not bring its capacity to that of its peers.

Figure 65: Capacity and Voltage Properties of Commercialized LIBs

		Nominal	Voltage (V)	
Manufacturer	Chemistry	Capacity (Ah)	*Min.*	*Max.*
Kokam Co.	NMC	12	2.7	4.2
LG Chem Ltd.	LMO-NMC	5.3	2.5	4.2
SAFT	NCA	7	2.3	4
LiFeBATT, Inc.	LFP	8	2	3.65

Source: Eddahech *et al.*, 2015

2. Mixing LMO with Al-doped $LiNiO_2$ has had some impressive results. We know that aluminum (Al) increases cell voltage and thermally stabilizes the $LiNiO_2$ somewhat. This has been used by AESC, the battery manufacturer of the Nissan Leaf however they also included an NMC layer in order to improve cyclability.

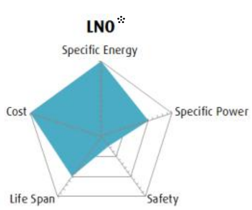
The Search Continues for the Perfect Cathode

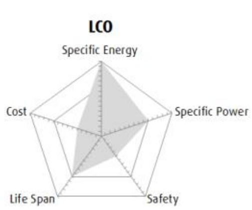
It is no wonder that with the complications that occurred with LMOs even when blended with NMC chemistry, battery designers are re-examining another well-researched cathode called the lithium nickel oxide (LNO) battery. Sure it seemed untameable and frequently exploded, but the LCO and the LMO chemistries just did not succeed and if the current wave of the EV market were to continue its upward trend, new battery chemistries would have to be evaluated and quickly brought to market. Thus, as research still continues to remedy the "manganese problem" in blended chemistries, there has been a concurrent trend to produce and enhance a nickel-rich cathode (NMC and NCA) that does not have the same issues.

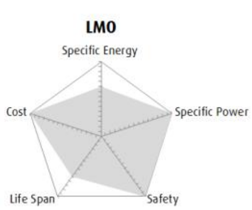
3. LITHIUM NICKEL OXIDE (LNO)

→ The Birth of Nickel Rich Chemistries (NCA and NMC)

Summary of limiting factors:







- LNOs appear to release more oxygen at a much lower temperature than LCOs, meaning that they are *even less* tolerant to abusive conditions.
- LNOs are difficult to produce due to the instability of the Ni^{3+} ions at elevated temperatures leading to debilitating phase transitions that produce a defective product to begin with.
- Charging causes the formation of Ni^{2+} ions that competes with intercalating lithium ions as they have similar atomic radii (0.76 Å for Li^{+} versus 0.69 Å for Ni^{2+}). This reduces active material and changes the structural integrity of the cathode.

Discovered in 1954, the lithium nickel oxide ($LiNiO_2$ or LNO) has been extensively studied by the Jeff Dahn Research Group at Dalhousie University since the 1990s and is one of the reasons why this group now works with Tesla. Similar to the LMO, the introduction of nickel was widely seen as a way to eliminate cobalt from the mix. In fact, the LNO chemistry has been shown to eliminate the

*Source: Liu et. al., 2017, Battery University, BMO Capital Markets

LNOs are even less tolerant to abusive conditions than LCOs

overcharge issues and the side reactions seen with cobalt and manganese with the electrolyte. However, while LNOs have some clear advantages, such as a higher energy density, lower decomposition temperature, and much lower cost, extensive research has concluded that serious destabilizing factors *eliminate it from being the sole transition metal in the cathode*. In particular, it appears to release oxygen at a much lower temperature than LCOs do, meaning that *it is even less tolerant of abusive conditions*.

Figure 66: Comparisons of LCO, LMO and LNO cathodes

	LCO	LMO	LNO	LFP
Cost	Expensive	Moderate	Cheap	Cheap
Decomposition temperature (ºC)	340	275	250	950
Exothermic peak temperature (ºC)	367	302	348	289
Exothermic heat flow W/g	20	7	33	-6
Environmental Pollution	Very Toxic	Good	Toxic	Good

Red: Bad ▪ Purple: Good ▪ Blue: Excellent

Source: Xu *et al.* 2015

LCOs and LNOs share a lot of the same physical and chemical characteristics and research has shown time again that nickel and cobalt are the best transition metals to use in the cathode because lithium ions can take in and release lithium ions more readily than other cathode materials. They also have a similar theoretical capacity of ~275mAh/g. However, LNOs have the edge when it comes to a higher capacity of more than 160mA/g in a voltage range of 2.5-4.1V, an excellent cycle life that performs well even when overcharging and deep discharging. However, nickel-oxide is not as stable as cobalt oxide and there are other issues to contend with that have impeded its use commercially.

i. Difficult to Produce a Stable LNO Cathode in the First Place

Research has shown that nickel and cobalt are the best transition metals to use in a lithium-ion battery, but LNOs are more difficult to produce

We noted earlier that LCOs are easy to produce, but LNOs are not as they are difficult to produce due to the instability of the nickel ions at the elevated temperatures required during the production process. The number of phase changes challenges the production process and the end product is defective from the get go.

A Little More Detail for the Scientifically Inclined

Obtaining a Homogenous LNO Cathode

This is perhaps because d-orbitals of the $Ni^{3+/4+}$ ions do not overlap with the oxygen orbital the way the Co^{4+} d-orbital does, permitting a more even intercalation process without the release of oxygen. However, nickel in the $LiNiO_2$ format is not as homogenous as $LiCoO_2$ and the behaviours of the Ni^{2+}, Ni^{3+}, and Ni^{4+} ions within the system means that the reactions are much more volatile. While *both* Co^{3+} and Ni^{3+} ions undergo phase transitions from hexagonal (active) to cubic (non-active) during production, *in the LCO this is completely reversible* whereas $LiNiO_2$ exhibits only slow partial reversibility, making the production of a homogenous LNO cathode difficult. In fact, it is *currently not possible* to produce a stoichiometric $LiNiO_2$ cathode as the real formula for $LiNiO_2$ is actually $Li_{(1-x)}Ni_{(1+x)}O_2$ where x~0.2, meaning that there is *excess nickel in the mix* that cannot be removed. Although using low temperature synthesis methods has produced a product that is close, the many phases shown in the figure above demonstrate that *the electrochemical properties of LNOs are tied to its production*.

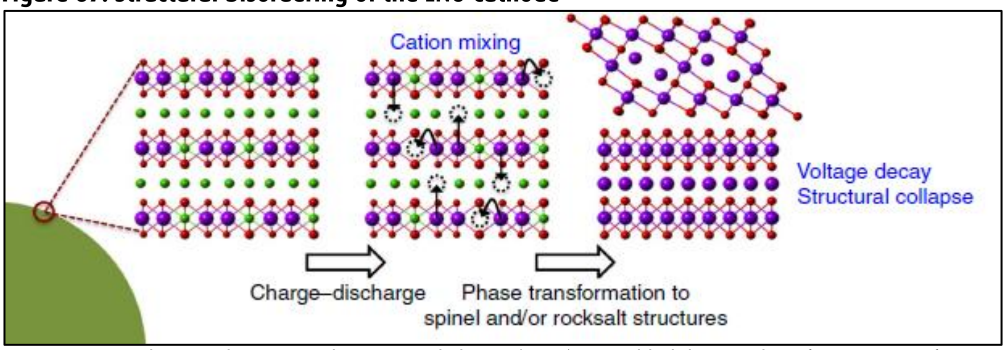
Sources: Kanno *et al.,* 1994, Chen *et al.,* 2014, Schipper *et al.,* 2017

ii. LNOs Are Susceptible to Structural Disordering, Leading to Degradation

One of the main problems with LNOs is that they are subject to *structural disordering reactions* as the battery is being charged and discharged. Nickel ions that are released from the cathode during the normal course of operation are the same size as the lithium ions and therefore they start to compete for the same spots in the cathode, creating a disordered pattern of nickel and lithium ions within the cathode. The nickel ions remain permanently in the cathode and that spot now becomes permanently closed. This means that the lithium ions can no longer be inserted into the cathode and there is less and less energy and capacity available to power the vehicle.

As the mixing increases, the cathode cannot retain as much lithium (green) and the holes eventually become permanently closed with Nickel (purple)

Figure 67: Structural Disordering of the LNO Cathode



Source: Kim, S, Cho, W., Zhang, X., Oshima, Y. and Choi, J. (2016). *A stable lithium-rich surface structure for lithium-rich layered cathode materials*. Nature Communications; DOI: 10.1038/nscomms13598.

iii. Thermal Instability Creates a Dangerous Situation

These processes also create heat at an increasing rate as the mixing becomes more pronounced, oxygen is released as the heat approaches 200˚C and the cathode becomes more and more un-structured at a quicker pace. At 220˚C, nickel ion reactions create more oxygen (~25% versus ~17%) than cobalt ion reactions at a lower temperature. This means that LNOs are more unstable than LCOs.

A Little More Detail for the Scientifically Inclined

The Formation of Ni^{2+} Competes With Lithium Ions and Releases Oxygen

Ni^3+ starts to reduce to Ni^{2+} after the first charge and as more and more Ni^{2+} is formed, the ions proceed to compete with intercalating lithium, as they have similar sizes (atomic radii 0.76 Å for Li^+ versus 0.69 Å for Ni^{2+}), resulting in slower lithium transport. Figure 68 shows that this creates a mix of Ni^{2+} and Li^+ ions inside the cathode instead of Li^+ alone, causing structural changes. Furthermore, once the Ni^{2+} ions are in the Li^+ sites they reduce to smaller Ni^{3+} ions causing local shrinkage around them and, thus, permanently blocking Li^+ ions from entering the cathode. This leads to capacity fade because the disordered material becomes more contracted and as more and more holes become permanently closed, the intercalation of lithium becomes impeded at an increasing rate.

Since Ni^{3+} is more readily reduced to Ni^{2+} ions than Co^{3+} and the subsequent structural changes, **more oxygen** is produced leading to **a much faster combustion reaction** than LCOs at lower temperatures. This is why LNOs have about the same exothermic peak temperature as LCO batteries, but have a much higher exothermic heat flow (33 compared to 20 for LCOs).

The Production of Oxygen as LCOs and LNOs Degrade into a Combustion Reaction

$$Li_{0.5}CoO_2 \longrightarrow \frac{1}{2} LiCoO_2 + \frac{1}{6} Co_3O_4 + \frac{1}{6} O_2 \qquad (240°C)$$ Oxygen production ~ 17%

$$Li_{0.5}NiO_2 \longrightarrow \frac{3}{2} Li_{0.33}Ni_{0.67}O + \frac{1}{4} O_2 \qquad (220°C)$$ Oxygen production ~ 25%

Sources: Arai *et al.,* 1998, Chen *et al.,* 2014, Vetter *et al.,* 2005, Schipper *et al.,* 2017

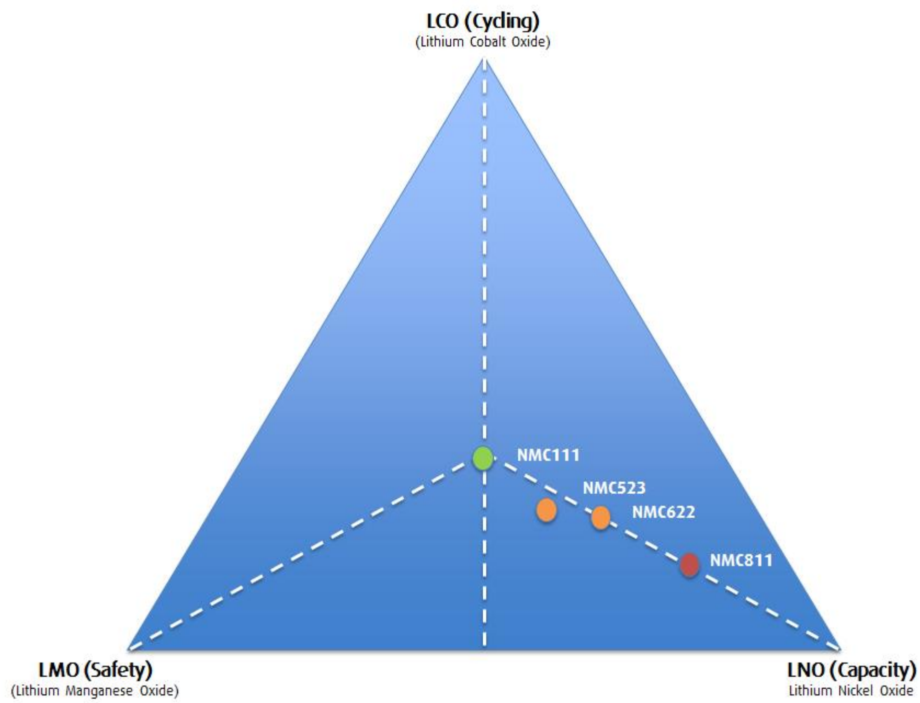
Ultimately, the solution to the nickel problem was to combine it with other transition metals that can stabilize it. Adding cobalt and manganese or doping the cathode with aluminum led to the creation of the NMC and NCA batteries.

WAIT A MINUTE! We just explained the problems of cobalt, manganese and nickel alone in the battery chemistry and scientists really decided to put them altogether? Are they crazy? How is it possible that the NMC811 battery chemistry is being touted as the next big thing?

To recap: the motivation to increase nickel content is to reduce the overall cost by cutting cobalt content without compromising performance. However, we know that nickel only LNOs are more unstable than cobalt-only LCOs. We also know that cobalt has its own unappealing properties from a chemistry perspective as it is volatile in overcharging situations and higher charge currents. Furthermore, the addition of manganese to the mix with its own issues makes figuring out the right combination of these elements very challenging.

We are now going to answer the question as to why these elements were combined in the first place. [Hint: cobalt and manganese stabilize nickel in different ways].

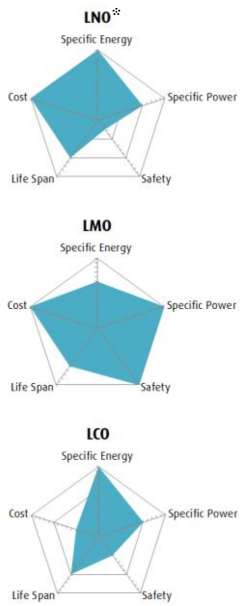
Figure 68: The Rate, Safety, and Capacity Compromises → Again, Preferred Performance Very Difficult to Achieve as Trade Offs Occur



Source: Schipper *et al.,* 2017, BMO Capital Markets

4. LITHIUM NICKEL MANGANESE COBALT (NMC)

→ Mixing Nickel, Manganese and Cobalt – Not That Crazy



Summary of limiting factors

- Cobalt and manganese stabilize nickel in different ways, but getting the right mix is very complicated as they could be combined in ways that could be dangerous → there is yet again a trade-off between electrochemical properties and stability.
- As nickel content increases over 70%, energy density goes up, but safety goes down
- Cannot remove cobalt entirely and our research suggests that NMC concentrations must contain at least 15-20% cobalt to hinder the mixing problem.

NMC batteries represent a group of chemistries with various ratios of Li, Ni, Co, and Mn (the actual chemical format is $LiNi_xMn_yCo_{1-x-y}O_2$). For example, NCM111 would have a chemical symbol of $Li(Ni_{1/3}Mn_{1/3}Co_{1/3})O_2$ meaning that the molar ratios of Ni, Mn, and Co are equal. Other combinations have more nickel content than Co and Mn, and therefore, are referred to as “nickel-rich” NMC cathodes. NMC532 would have 50% Ni, 30% Mn and 20% cobalt. Many also use the acronym NCM to describe this chemistry. First and foremost, we are going to dive right in to how cobalt and magnesium stabilizes nickel.

i. The Addition of Cobalt Eliminates the Structural Disordering Problem

Cobalt oxide is more stable than nickel oxide and when ~20% is added to the cathode, the formation of the nickel ions that proceeds to compete with lithium ions stops. This means that the mixing issue described earlier is inhibited. But simply increasing cobalt content is not the answer as cobalt must be constrained because of its ability to produce oxygen gas in overcharge situations. Even in an NMC111 battery where cobalt concentrations are 33%, there was evidence of an overcharge region where the current changes to an ohmic one and generates a lot of heat. However, the overage threshold did increase to 180% for NMC111 versus a 150% threshold for the LCO chemistry.

ii. The Addition of Manganese Also Improves Stability

Manganese improves the structural stability of the nickel as it is unstable from the get-go. Since the nickel-only cathode releases oxygen, manganese also prevents the release of oxygen meaning that the thermal instability seen in nickel-only cathodes is considerably reduced. However, at higher manganese concentrations, the capacity is reduced to 110mAh/g and the voltage becomes constrained in the 3-4.15V range. Again, it’s a little bit of manganese, but not too much!

Source: Liu et. al., 2017, Battery University, BMO Capital Markets

A Little More Detail for the Scientifically Inclined

Cobalt Content of at Least 20% Reduces the Structural Disordering Problems

Extensive research has shown that Co^{3+} is quite stable compared to Ni^{3+} in mild conditions because Ni^{3+} is in a low spin state that destabilizes the structure (Jahn-Teller distortions). Since they shared many of the same properties, the use of cobalt in the LNO mix was evaluated. Sure enough, it was found that adding Co^{3+} or creating a $LiCo_{1-y}Ni_y$ cathode where 0>y>0.8 stabilized the Ni^{3+} ions by inhibiting the formation of the Ni^{2+} thereby reducing/eliminating the mixing problem discussed earlier. This means that cobalt content of at *least 20% eliminates the structural disordering issue* and greatly reduces the capacity loss seen in the LNO chemistry [i.e. Co/(Ni+Co)>0.2]. Furthermore, it has been shown that cobalt content of 30% created a stoichiometrically stable cathode or $LiNi_{0.7}Co_{0.3}O_2$ thereby eliminating the excessive nickel problem at the production stage. By contrast, at 80% Ni and 20% Co, the crystal structure phase changes that were seen in LNOs due to the presence of Ni^{4+} still existed.

Manganese Improves Thermal Stability in the Discharged State

Manganese (Mn) also exhibits similar structural stability in limiting the distortions (Jahn Taller Effect) of Ni^{3+}, but it not as cut and dried as some Ni^{2+}/Mn^{4+} forms instead of the desired Ni^{3+}/Mn^{3+}combinations. Furthermore, the disproportionate reaction of Mn^{3+} ions under acidic conditions also introduces a major limitation. Compared to other batteries, lithium-manganese-nickel oxide batteries tend to have a higher rate of Ni and Mn dissolution, which leads to severe capacity fade, especially at high temperatures. However, manganese still has its purpose here. When LNOs are completely discharged or the cathode is delithilated, the cathode can become rock solid and will initiate violent exothermic reactions at 200˚C. $Mn^{4+}$is actually stable in this mix and would not readily dissolve into Mn^{2+} as in the LMO chemistry. Therefore, adding Mn to the mix *improves thermal stability* in the discharged state and stabilizes the matrix, but higher concentrations *reduce* the reversible capacity to 110mAh/g and the voltage becomes constrained in the 3-4.15V range. Again, it's a little bit of manganese, but not too much.

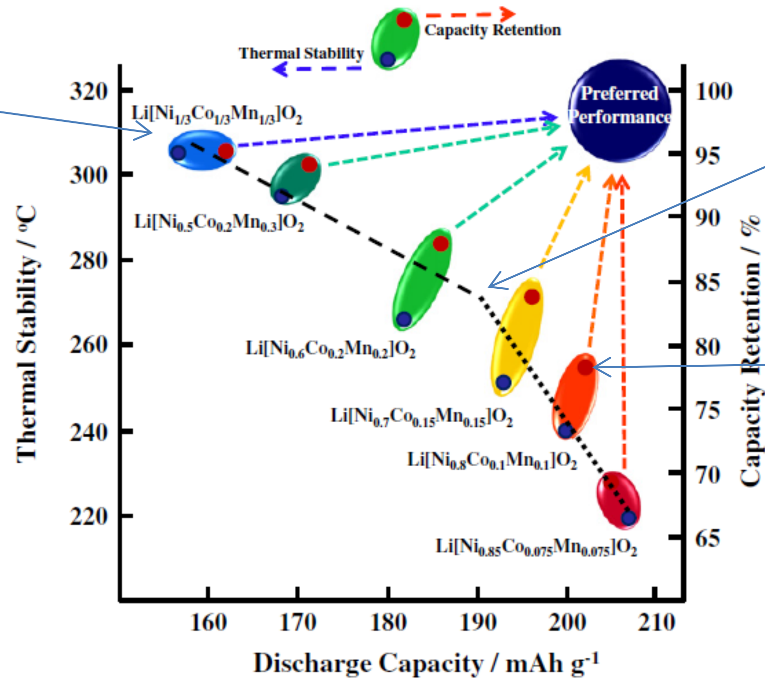
Sources: Zhecheva and Stoyanove, 1993; Arai *et al.*, 1998; Rougier *et al.,* 1996; Chebiam *et al.*, 2001; Pieczonka *et. al,* 2013; Song *et al.*, 2014; Nitta *et al.*, 2015; Bak *et al,* 2016; Myung *et al.,* 2016, Mauger and Julien, 2016; Manthiram *et al.,* 2017.

Therefore, the mixture of Ni (higher capacity), Co (better rate capability) and Mn (safety) makes sense. However, the use of higher nickel content still has issues despite being tempered by Co and Mn content and the technology needs to overcome some major technological hurdles to optimize these characteristics, which may or may not be possible.

This is how it all plays out. In these two prominent figures in the literature, we see that NMC111 and NMC532 look like pretty good compromises. The NMC111 chemistry that contains equal parts Ni, Mn and Co has been commercialized for some time, but its capacity of 155Ah/kg is too low for today's BEVs. But looking at the discharge capacity, we see that the energy density is still an issue. Furthermore, the much-touted nickel-rich chemistry NMC811, shows poor thermal stability and capacity retention tests.

Figure 69: Thermal Stability and Capacity Retention Erodes Quickly With Increasing Nickel Content

Our NCM 333 (aka NCM111, NMC111or NMC333) looks like a good compromise, but it does not have the capacity needed to increase vehicle range

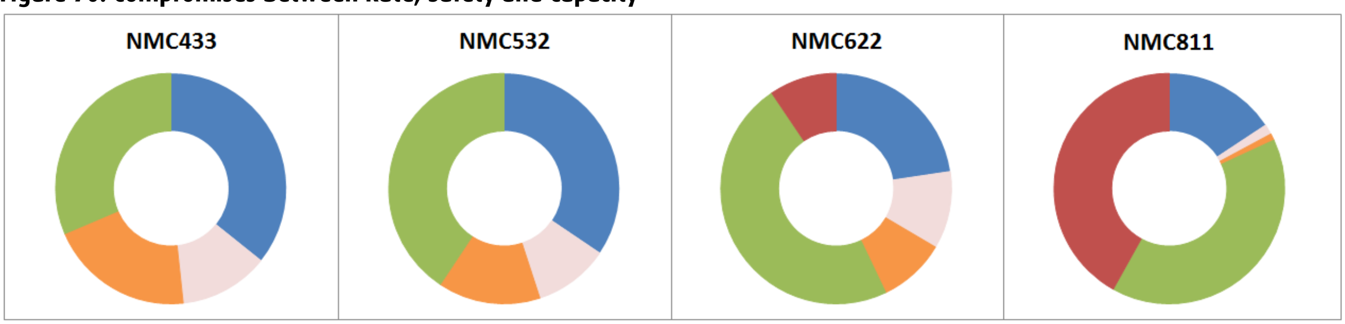


Capacity retention and thermal stability starts to decrease at an increasing rate as nickel passes the 60% mark

Yikes!

Reprinted from Journal of Power Sources, 233, Noh H., Youn, S., Yoon C. and Sun, Y. *Comparison of the structural and electrochemical properties of layered $Li[Ni_xCo_yMn_z]O_2$ (x=1/3,0.5,0.6,0.7,0.8and 0.85) cathode material for lithium-ion batteries.* p.121-130, 2013, with permission from Elsevier.

Figure 70: Compromises Between Rate, Safety and Capacity



NMC433	NMC532	NMC622	NMC811
- Thermal Stability ~305°C - Capacity fade 95% - Discharge 160mAh/g - ↑ Oxygen gas from 30% Co - Mn^{3+} Disproportionation rxn	- Thermal Stability ~295°C - Capacity fade 95% - Discharge 160mAh/g	- Thermal Stability ~265°C - Capacity fade 87% - Discharge 185mAh/g -20% Mn cause phase change - Increase in O_2 release	- Thermal Stability ~240°C - Capacity fade 78% - Discharge 200mAh/g - Structural Disordering - 10% Mn = ↑ phase change - Reduction in reversible Li^+ - Increase in O_2 release
Phase Changes: Layered →spinel	Layered →spinel	Layered →spinel →rock salt	Layered →spinel →rock salt

blue: excellent ▪ orange: very good ▪ pink: good ▪ green: not ideal ▪ red: dangerous (blow up)

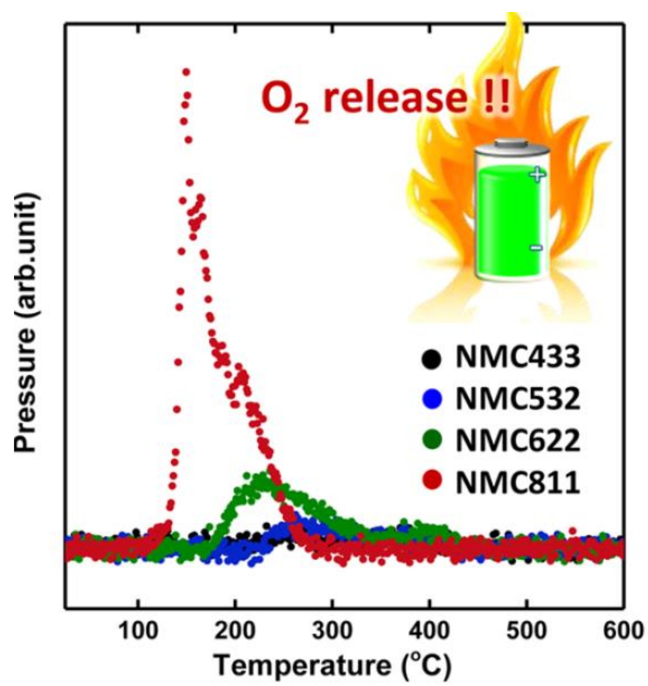
Source: Bak et al., 2016 and other scientific literature, BMO Capital Markets

Finding the Right Combination of Nickel, Cobalt and Manganese → NMC(???)

NMC cathodes have been touted as a replacement of LCO batteries, as they are cheaper. To recap, each element has its strengths and weaknesses: 1) Nickel may have high capacity, but low thermal stability; 2) Cobalt has great electronic conductivity and cycling within a confined range, but also loses on the thermal stability side and has lower capacity; and 3) Mn has great safety, but lower capacity and performance. However, because of the dangerous structural disordering problem and ability to produce oxygen more easily at lower temperatures, **we can conclude that the trade-off between safety and capacity *lies with nickel content*.**

From the extensive work on LNOs detailed earlier, we know that achieving a high capacity means a compromise on safety as nickel-only cathodes are even more unstable than cobalt-only cathodes. Figure 69 shows that as nickel rises in the 60-70% range, the thermal stability and capacity start to degrade more quickly. Furthermore, at an 85% Ni there may have been a high discharge capacity of 208 Ah/kg but there was a *very rapid capacity loss* after 100 cycles retaining only 55.6% of its capacity compared to 92.4% for the NMC111. Therefore, there *are strong linear relationships between increased nickel content, safety and capacity that fade* even with cobalt and manganese, tempering some of the issues seen in LNOs

Figure 71: The Propensity of NMC811 to Release O_2 at Elevated Temperatures



Reprinted (adapted) with permission from Bak et al. (2016). *Structural Changes and Thermal Stability of Charged $LiNi_xMn_yCo_zO_2$ Cathode Materials Studied by Combine in-situ Time Resolved XRD and Mass Spectroscopy.*
Applied Materials and Interfaces; 6:22594-22601.© 2013 American Chemical Society

A Little More Detail for the Scientifically Inclined

Increased Ni^{2+}Results in Capacity Fade and Increased Ni^{4+}Leads to Instability

Specifically, the amount of Ni^{2+} is the leading cause of lithium loss and capacity fade here and the amount of unstable Ni^{4+} in the cathode in the charged state is the main cause of thermal instability. However, it is technically impossible to stop the formation of Ni^{2+} and Ni^{4+} in the system (i.e. stabilize the desired Ni^{3+}). Specifically, as nickel becomes the more active element in the process, it switches between the Ni^{2+}, $Ni^{3+}$and Ni^{4+} ion states via redox reactions ($Ni^{2+} \leftrightarrow Ni^{4+}$) much quicker. When the battery is being charged at a high SOC or in an overcharged state (i.e., the cathode is highly delithilated or does not contain any lithium), there are more of the very unstable Ni^{4+} ions that quickly reduces to Ni^{3+}then Ni^{2+} state releasing oxygen.

The main issue here remains *the propensity of nickel ions to readily reduce/oxidize between the Ni^{2+}, $Ni^{3+}$and Ni^{4+} states* leading to thermal stability and capacity fade.

Source: Dahn *et al.,*1994; Noh *et al.,* 2013; Bak *et al.*, 2016; Schipper *et al.,* 2017.

i. Increasing Thermal Instability With Increasing Nickel Content

The liberated oxygen that forms as nickel ions move back and forth between ionic states reacts with the electrolyte and causes the consumption of active materials including lithium and gas evolution (O_2 and CO_2). If the electrolyte has been heated past its flash point, these reactions can cause thermal runaway and catastrophic failure.

Heat also causes phase changes from the original ordered layered structure to a disordered spinal structure that becomes more and more rigid until it forms a rock salt structure. Once in the rock salt phase, it again becomes prone to exothermic reactions. Again, this phase change phenomenon is directly related to nickel content. Although manganese tempers this, researchers at the Brookhaven National Laboratory found that nickel concentrations 60% and induce mechanical instability as well as cracking at the cathode, causing faster degradation of the battery. There is also evidence that cobalt can stabilize phase changes and looking back at Figure 70, the NMC811 solidified at 375°C versus none for NMC622, which further backs up our believe that cobalt content should probably stay at the ~20% level.

ii. Increase in Oxygen Causes the Formation of By-Products

As Nickel concentrations get bigger there is increased formation of oxygen lithium by-products (lithium carbonate [Li_2CO_3] and lithium hydroxide [LiOH]) on the cathode surface. This is disruptive in the following ways: 1) lithium hydroxide reacts with the electrolyte *causing an acid attack* of hydrofluoric acid on the cathode; and 2) lithium carbonate causes the *cathode to swell* especially as temperatures rise. Furthermore, it can trap lithium ions and impede them from doing their job of delivering energy. It has been demonstrated that at nickel concentrations of *more than 70%,* the presence of both compounds on the surface of the cathode increases dramatically.

Figure 72: LiOH and Li_2CO_3 Concentration Amounts on the Cathode and the Reduction in Capacity Retention With Increasing Nickel Content

Chemical Name	Industry Name	LiOH (ppm)	Li_2CO_3 (ppm)	Capacity Retention*
$Li[Ni_{1/3}Mn_{1/3}Co_{1/3}]O_2$	NMC(1,1,1) or (3,3,3)	790	1008	92.4%
$Li[Ni_{0.5}Mn_{0.3}Co_{0.2}]O_2$	NMC(5,3,2)	1316	1080	90.0%
$Li[Ni_{0.6}Mn_{0.2}Co_{0.2}]O_2$	NMC(6,2,2)	2593	2315	85.1%
$Li[Ni_{0.7}Mn_{0.15}Co_{0.15}]O_2$	NMC(7,1.5,1.5)	4514	6540	78.5%
$Li[Ni_{0.8}Mn_{0.1}Co_{0.1}]O_2$	NMC(8,1,1)	10,996	12,823	70.2%
$Li[Ni_{0.85}Mn_{0.075}Co_{0.075}]O_2$	NMC(8.5. 0.75, 0.75)	11,285	15,257	55.6%

*Capacity retention for each chemistry was measured after 100 cycles at 25°C
Note: After 100 cycles, NMC chemistries with 70% nickel content or more would have reached EOL
Source: Noh *et al.,* 2013.

iii. Increased Nickel Content Leads to the Return of the Mixing Issue

Earlier, we described the structural disordering or mixing that occurs because Ni^{2+} and Li^{+} ions have similar sizes. The increased competition during the intercalation process as well as the disruption in structural integrity leads to capacity fade and loss of active material. The research has shown time again that increasing the Ni/Co ratio will lead to more interlayer mixing. As the concentration of nickel increases and the cobalt concentration decreases below the 20% mark, cation mixing begins to increase.

Conclusion: Our Take on the NMC811 Battery

The battery industry is touting NMC811 as the "next big thing." However, the use of this chemistry has intense safety risks that will not be easy to alleviate. Furthermore, the capacity loss seen in as little as 100 cycles makes us very skeptical that this chemistry will be commercially viable over the next five to ten years. However, when we looked at the scientific literature on the NCA chemistry, we concluded that we would have probably said the same thing about the battery that is currently in Tesla cars and working quite well.

The NCA battery is actually still considered to be “dangerous” in many modern reviews of the LIB scientific literature because of its propensity to catch fire. But it still works and it is currently on the road. While there have been some accidents, the NCA chemistry is still, and continues to be, the battery of choice for Tesla’s Model S and Model X. So while we detailed substantial technical risks with the upcoming NMC811 battery, the NCA was able to be tamed through technical ingenuity and an excellent battery management system.

Therefore, **we include a small market penetration of 4% in 2025 in our models** and will maintain our NMC622 estimate of 60% penetration until we get a better sense of the expected roll out of the NMC811 battery by LG Chem and SK Innovation in the next couple of years.

Part IV –Range Anxiety and the Consumer Experience

Range anxiety – myth or reality? Ask anyone if range anxiety is a myth or a reality and you will get very divergent points of view. Some say it's a myth or worse a conspiracy. In 2016, MIT researchers found that 87% of car use could be replaced with a BEV without any problem. This number more or less has been touted in the media as an explanation for the slower-than-predicted BEV uptake.

The problem – the 13% that's not replaced by BEVs. When you think about it, it's not the 87% or so number that is the problem – it's the 13%. That 13% could be the 500km annual trip for one family or weekends at the cottage for another. Whether it is pilgrimages to different venues for sport tournaments or going to remote places for an outback adventure for another, that 13% is difficult to predict.

The challenge to consumers – ICE vs. BEV. Instead of deciding whether range anxiety is a myth or not, we are taking the approach that the decision-making process of a car purchase (budget, needs, style and insurance costs) is the same whether it's electric or not. Quite frankly, an ICE car represents 100% of everyone's individual needs, period. Going off road, there is an ICE for that. Large family, there is an ICE for that. Live in rural area with a lot of snow, there is an ICE for that.

Adding more time to long haul trips. How this plays out is simply that if you are taking a long haul trip (probably with children in tow) if you use your BEV, you have to map your route much more carefully, estimate your stopover time with much more precision and find out where the charging stations are on the road while making sure they are the right type.

Higher range and better variety of vehicles will increase market penetration

Consumers need increased range and newer types of EVs released. Our point is simply that range has to increase (and it is) and newer types of EVs (i.e. pickup trucks, vans, etc.) need to be released. Back in 2013, the California Center for Sustainable Energy found that only 9% would be satisfied with a BEV that can go 100 miles before having to charge again. Further, 70% would be satisfied with 200 miles, and GM has invested a significant amount of money to bring the first mass market vehicle that could meet this requirement. Indeed, 200 miles is considered the minimum threshold for wide-scale adoption and the rapid growth in sales of the Chevy Bolt is certainly a testament to this. But the problem would still not be completely solved here.

This section will be a deep dive on the problems encountered during the occasional heatwave, cold weather performance (range and charging issues) and the lack of public charging infrastructure.

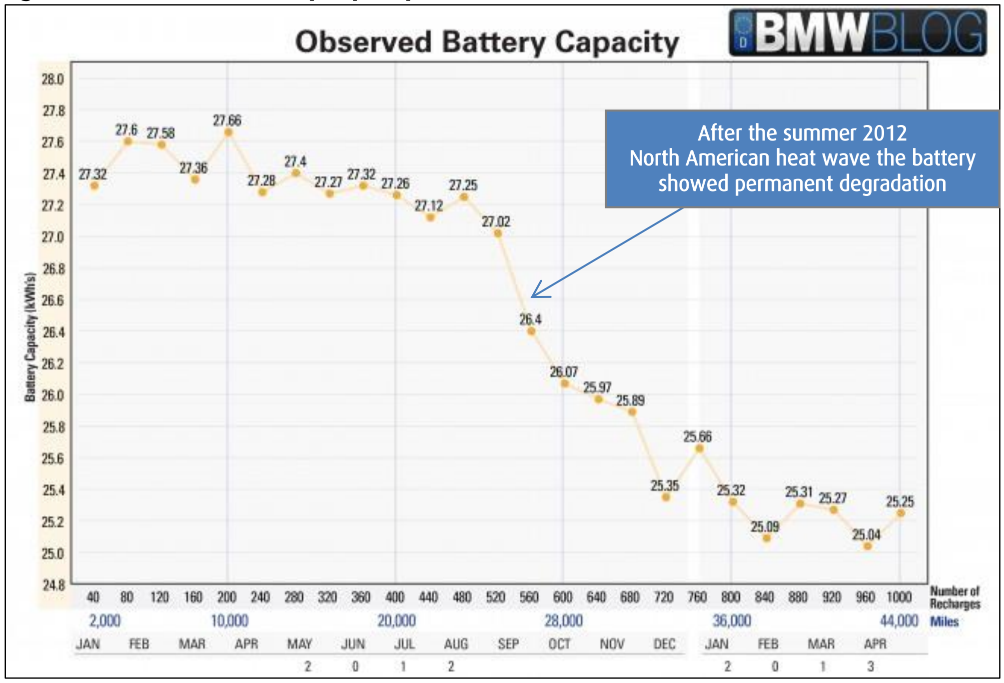
1. The Effects of Climate on Battery Performance

Extreme temperatures degrade the battery

Extreme temperatures are a serious impediment to EV market uptake. When the first wave of electric cars came out, one owner of a BMWi3 meticulously charted external factors such as temperature, speed, topographic conditions and distance for every trip. The data showed that there was steep irreversible decline in capacity that occurred after a very hot summer. Other BEV owners reported similar experiences as well as a reduction in range, especially in freezing temperatures.

Our research shows that these claims have unequivocal scientific merit and we believe that extremely hot or cold temperatures are a much greater problem than OEMs would like to admit. The performance and battery life are impacted especially when you add heating and cooling into the mix. Therefore, we believe that the impacts of extreme temperatures are also a serious impediment to EV market uptake.

Figure 73: Permanent Battery Capacity Loss After a Heat Wave



Source: InsideEvs

Extreme Temperatures Reduce Range and Lead to Battery Degradation

Researchers from Carnegie Melon University studied the direct effect of different climate conditions on battery performance and showed that freezing temperatures and desert-like conditions dramatically reduce range and catalyze battery degradation in a number of ways.

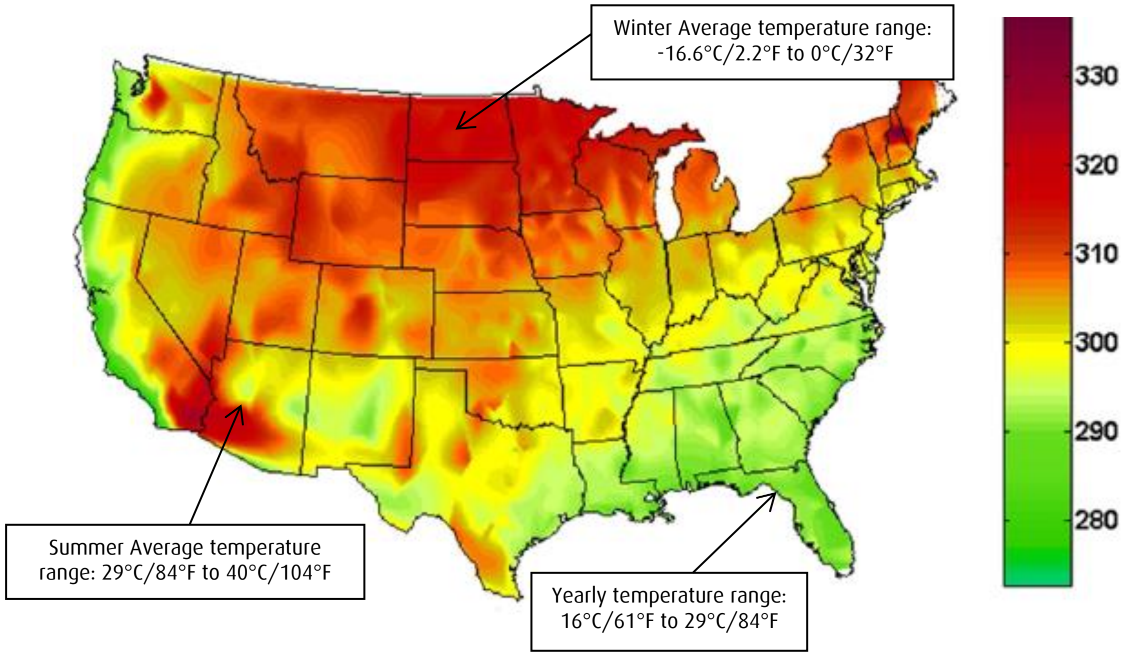
Optimal battery performance occurs only in mild climates. The AAA Automotive Research Centre routinely states in the media that there is a 33% decrease in range in extreme heat (35°C/95°F) and a 57% decrease at temperatures below freezing (-7°C/20°F). Figure 74 below shows how this plays out across different North American climates and indicates that optimal battery performance occurs only in climates with mild temperatures, such as in the southeast, particularly in Florida, and the Pacific coast. However, BEV drivers in other parts of the country, particularly in the Midwest and the North, have a few issues to contend with.

Electrochemical reactions involved in degrading battery:

-capacity/power fade
-self-discharge
-thermal runaway

Using driving in San Francisco as a base case where a greater-than-70-mile range was achieved 99% of the time, the researchers found that there was *a 29% decrease in range in Phoenix in the summer* and *a 39% reduction in Rochester, MN, in the winter*. While this reduction can be explained partly by the extra energy needed to maintain cabin comforts such as air conditioning on hot days, there are also a number of electrochemical reactions involved that degrade the battery. These include capacity/power fade, self-discharge, and thermal runaway. Furthermore, charging times have also been shown to be longer in the red areas of the map versus green areas and this has important implications for many that do not live in Southern California or Florida.

Figure 74: Suboptimal Temperatures Lead to Higher Energy Consumption (Wh/mi) and Decreased Vehicle Range



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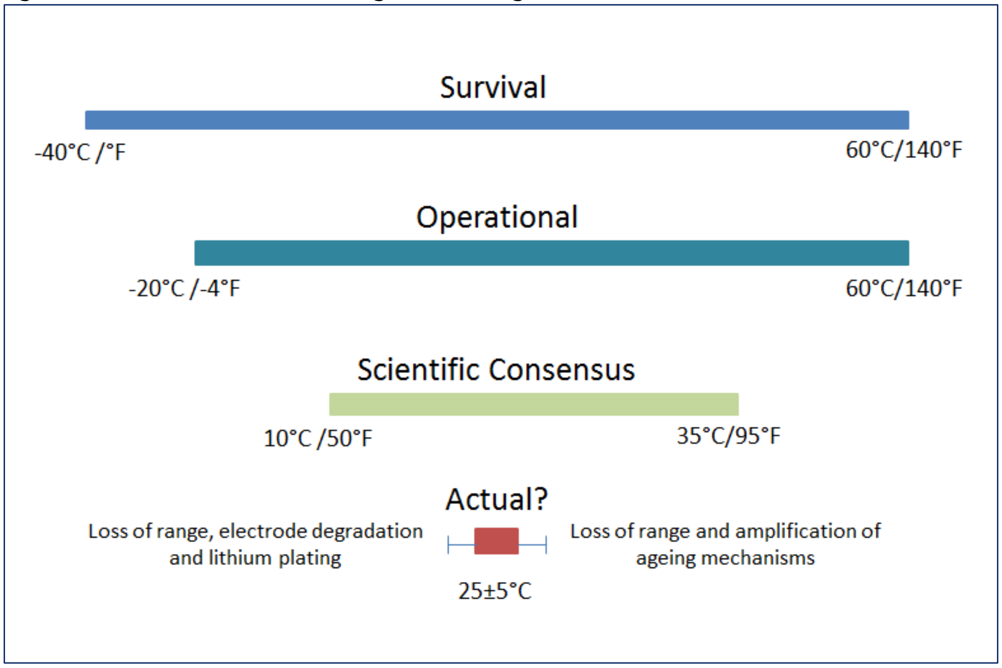
Optimal Operating Temperature Is a Moving Target

Manufacturers' operating temperature range doesn't match scientific consensus. While optimal operating temperature varies with battery types, manufacturers tend to specify an operating temperature of between -20°and 60°C (-4°F to 140°F). However, the scientific consensus is that the optimal temperature range is between 10°C and 35°C (50°F to 95°F) and numerous studies have shown that temperatures outside of that range have serious deleterious impacts on the battery. Moreover, new research shows that the range may be an even narrower subset.

Degradation rate increases as temperature move away from 25°C. Researchers at the ZSW in Germany found that rates of degradation begin to increase immediately as temperatures move away from the 25°C mark. Therefore, there is reason to believe that the optimal temperature range is even narrower. Performance aside, temperature is a leading factor of degradation mechanisms that can significantly reduce the lifecycle of the battery and the importance of heating and cooling systems cannot be overstated.

Survival means that it could still work at those temperatures, but it is not advisable to continually do so

Figure 75: Research Shows That Degradation Begins on Either Side of 25°C



Source: Walker, 2015, Waldmann *et al.,* 2014, BMO Capital Markets

High Temperatures Are Not Kind

- Increased capacity fade from loss of active lithium and electrode materials
- Increased impedance causing a reduction in power density
- Reduced cycle performance (i.e., charging/discharging) at an increasing rate
- Solutions such as coating electrodes have been beneficial, but the battery management system is still the key to prevent thermal runaway.

Lithium batteries do not like heat. All regular technology users know that lithium batteries do not like heat and the reality is no different for BEV drivers. A common meme among first wave BEV drivers is that "sun is evil." At extremely high temperatures (~50°C), especially at a high state of state of charge (SoC), recoverable power and capacity are significantly reduced. Furthermore, A/C usage on hot days can be problematic since it is typically the largest energy hoarder in the vehicle. This means that parking a BEV in a sunny parking lot while at work could leave you stranded on the drive home. But a decrease in range is not the only issue.

High ambient temperatures amplify degradation and the battery loses capacity sooner than expected

High temperatures amplify typical aging mechanisms. High temperatures tend to amplify typical aging mechanisms, such as transition metal dissolution and increased resistance. Research has shown that the rate of storage capacity degradation increases from ~4.22% to ~13.24% and the resistance increases from 49.4% to 584.1% after about 260 cycles. As temperatures rise, the dissolution of active materials on the surface of the electrodes becomes faster and the battery self-discharges while in storage especially at high states of charge (SOCs). Manganese in particular becomes much more reactive. Common recommendations include end users store vehicle in a garage that is dry and clean with good ventilation, avoid direct exposure to sunlight and keep significant heat sources about two meters away.

Battery management systems are key to prevent overheating of the battery

Battery management system (BMS) – not ideal for cars. Researchers have also looked at coating the electrode materials and making the electrolyte more resilient, but with little success. The main strategy continues to be using the battery management system (BMS) to control the battery's safety vents and thermal fuses. Once the temperature reaches a threshold, usually the temperature of the separator, the BMS shuts down the battery and resets it once it has cooled. This may be fine for small electronic devices, but having a car shut down on the highway also puts passengers in danger.

Within the battery, heat causes a number of chemical reactions. As the temperature rises, the speed that lithium ions go back and forth increases. This speed becomes different than the rate that the electrodes can accept them. As they "hang around" and wait their turn to go into the electrode, they start to react with other components of the cell in various side reactions. Namely, lithium ions begin to plate the anode (a precursor to dendrite formation) causing loss of function.

Cathode materials also start to degrade. We know that manganese ions from NMC and LMO cathodes react with the electrolyte or can leach and migrate towards the anode, where it contributes to plating the surface of the anode or reacts with the electrolyte. The reactions tend to attack the lithium ions meaning that the battery itself becomes less efficient. This leads to irreversible capacity loss.

The Rumours Are True – BEVs Don't Perform Well in Cold Temperatures

- Cold weather performance is a significant barrier to mainstream acceptance especially in Canada, the U.S., and Scandinavia.
- Increased discharge rates mean that range is reduced much more than with elevated temperatures and there is an increased risk of being stranded.
- Slowdown in electrochemistry (particularly the charge transfer kinetics) increases the risk of lithium plating and causes extensive resistance. The deposition of metallic lithium on the graphite anode is a precursor to thermal runaway.
- Charging repeatedly in cold weather significantly reduces the lifespan of the battery.

In colder temperatures, the battery will self-discharge faster meaning that BEV drivers could be left stranded

Cold weather – 40-60% decrease in range for BEVs. While gasoline cars are roughly 20% less efficient in cold weather, BEV drivers report a 40-60% decrease in range. From a consumer perspective, this is a critical hurdle as people would have amplified range anxiety in the winter months. In fact, there are plenty of blogs filled with recommendations on how to improve range in the winter months. But there is little that can be done at this level because the components of the battery change their overall behaviour in freezing temperatures. At -7°C and -20°C researchers have found that there is a 20% and 40-45% reduction in range, respectively, and an astonishing 70% decrease at -20°C. Furthermore, cabin heating resulted in an additional loss of 25% or more as temperatures dipped below the -7°C mark, and a 60% decrease in range at -20°C.

But It Gets Very Cold in Norway! What Norwegian Experience Teaches Us

Norway one of the leading EV markets – but incentives not the whole story. Norway is one of the leading EV markets, with EVs accounting for 42% of total new car sales in 2017, far outpacing other countries in the European Union. Furthermore, Oslo is the EV capital of the world with the highest EV density per capita. Yet it has one of the coldest climates on the planet raising the question why are EVs so popular? While the wide variety of incentives offered (e.g. zero purchase and VAT taxes, free toll roads, free municipal parking and access to bus lanes)[1] is the principal driver of growth, we believe that this still does not explain their popularity given the reductions in range in cold weather described above.

Most households have ≥ two cars – EV used for local commute. A little sleuthing revealed that 85% of households had two or more cars and that an electric model was *only one of them*. The typical driver is a middle-aged father using an EV for the morning commute. The remaining 15% of drivers that had a BEV as their only vehicle cited the expensive government tax on gas cars as the main reason for purchase and relied on car-sharing gas cars or public transit in colder temperatures and for longer road trips. In other words, cold weather performance is another impediment to full-scale adoption.

The Impacts of Cold Weather on Lithium Ion Batteries

The consensus in the scientific literature is that the reduction in range is due to a *slowdown* in the speed at which the lithium ions go back and forth. This slowdown reduces the conductivity of the electrolyte and decreases the intercalation process into the anode. In other words, everything slows down leading to faster discharge rates than those seen with elevated temperatures.

Energy capacity is drastically reduced in cold weather and worsens as the temperature drops and battery efficiency decreases causing discharging to become faster. The first issue is increasing self-discharge while in storage in cold temperatures compared to optimal. This means that if the car is parked outside at work, the cell will self-discharge faster. There is also a serious safety factor to consider. Cold weather, particularly when charging, increases the risks posed by lithium plating — a precursor to thermal runaway.

At first, it was believed this reduction was due to the electrolyte and designers focused on developing a more carbonate-based electrolyte solution to make mobility easier in colder temperatures (EC, EMC, DMC, etc.) [2]. However, this turned out to be a small contribution to the overall issue. Scientists then looked at the high charge transfer resistance and found that it was *the slower intercalation process at the graphite anode that was the problem, as it increased the likelihood of lithium plating*. A pre-cursor to dendrite formation, lithium plating is a problem that becomes more pronounced when charging at cold temperatures and therefore, is discussed in the next section.

Solutions to the Low Temperature Threshold

Our research suggests three potential solutions to the low temperature threshold that are currently being considered. They are changing the battery design, improving battery management systems, instituting a climate grading system and cabin preconditioning.

Changes to Battery Design

In a study by the Université du Québec at Trois-Rivières, developing an electrolyte that has a much lower freezing point and higher conductivity in colder temperatures as well as improving the

[1] The Norwegian parliament guarantees the purchase incentives until 2018 or until there are 50,000 zero emission cars on the road. On average, 500 electric cars are purchased each month. The Norwegian Electric Vehicle Association has set a goal of 100,000 electric cars within 2020.

[2] EC = ethylene carbonate; EMC=ethyl methyl carbonate; DMC = dimethyl carbonate

lithium insertion into the graphite anode would be the most beneficial to improve cold weather performance. Again, changing any one of these parameters is not easy.

Improving Battery Management Systems

The battery management system (BMS) is essentially 'the brains' behind the battery. It ensures that the battery does not get overheated. OEMs employ a number of different battery management systems yet the outcome remains the same; to prevent thermal runaway and manage the temperature of the system. As we know from our previous discussion, most LIBs have an optimal range of about 10°C and 30°C and outside of that range, the battery cells within the pack need to be maintained within that range. An optimal BMS should be designed to maintain a temperature difference of about 5°C between cells. However, this is difficult to achieve and again, there are trade-offs as to the different types of systems that can ensure temperature performance.

Figure 76: Trade-Off Analysis for the Actual Battery Thermal Management System

	Forced Air	Liquid	Heat Pipe	PCM	Thermoelectric	Cold Plate
Ease of use	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Integration	Easy	Difficult	Moderate	Easy	Moderate	Moderate
Efficiency	Low	High	High	High	Low	Medium
Temperature Drop	Small	Large	Large	Large	Medium	Medium
Temperature Distribution	Uneven	Even	Moderate	Even	Moderate	Moderate
Maintenance	Easy	Difficult	Moderate	Easy	Difficult	Moderate
Life	> 20 years	3-5 years	> 20 years	> 20 years	1-3 years	> 20 Years
Initial Cost	Low	High	Moderate	Moderate	High	High
Annual Cost	Low	High	Low	Low	High	Moderate

Source: Jaguemont et al., 2016

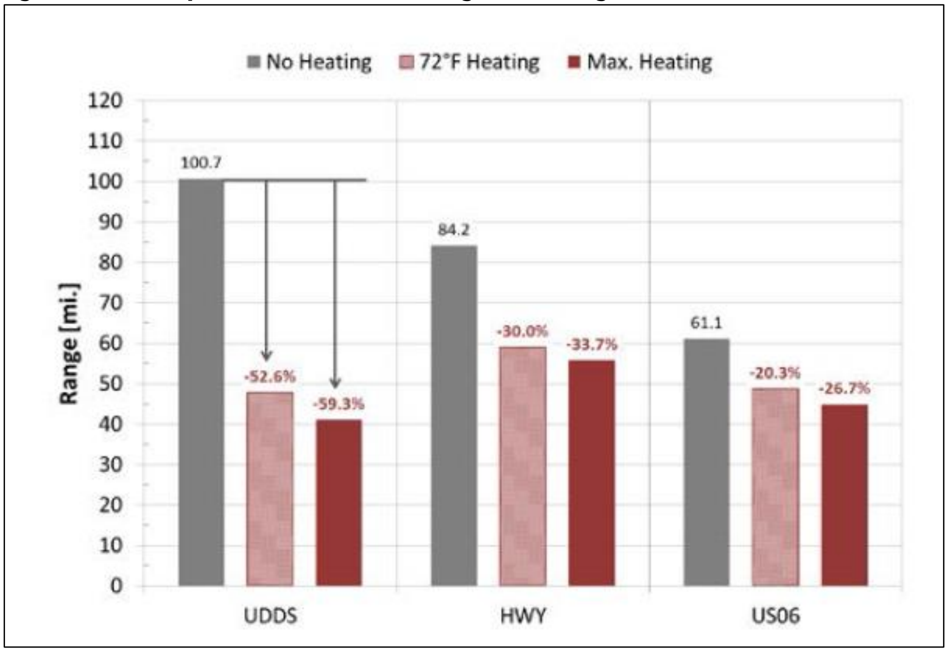
Institute a Climate Grading System

Some battery chemistries are not as affected by cold temperatures as others. For example, a battery that contains the expensive lithium titanium anode is the best cold weather performer. Therefore, a climate grading system would provide better fleet management, as the typical EV is meant for southern California weather, not the snowy freezing temperatures of most climates.

Cabin Pre-Heating or Pre-Cooling Improves the Efficiency of the Fleet

The reduction in range is greater in colder temperatures than in the hotter range as heating takes up much more energy than the A/C compared to ICE vehicles. This is because ICE engines are wasteful and the extra heat generated by the engine facilitates cabin heating. Tests at the Argonne National Laboratory's Advanced Powertrain Research Facility found that heating the cabin that was about 20°F (-6°C) caused a 20-59% reduction in range compared to no heating. This reduction in range can be improved tremendously by cabin preconditioning such as pre-heating or pre-cooling. As such, there are smart phone apps that will pre-condition the car when the battery is still plugged in to a charging station so warming the cabin will not impact the battery pack.

Figure 77: The Implications of Cabin Heating on BEV range



US EPA mandated dynamometer tests on fuel economy

UDDS – Urban Dynamometer Driving Schedule represents the cycle conditions for light duty driving vehicle testing (aka city driving).

HWY – Highway driving conditions under 60m/h or 100km/h

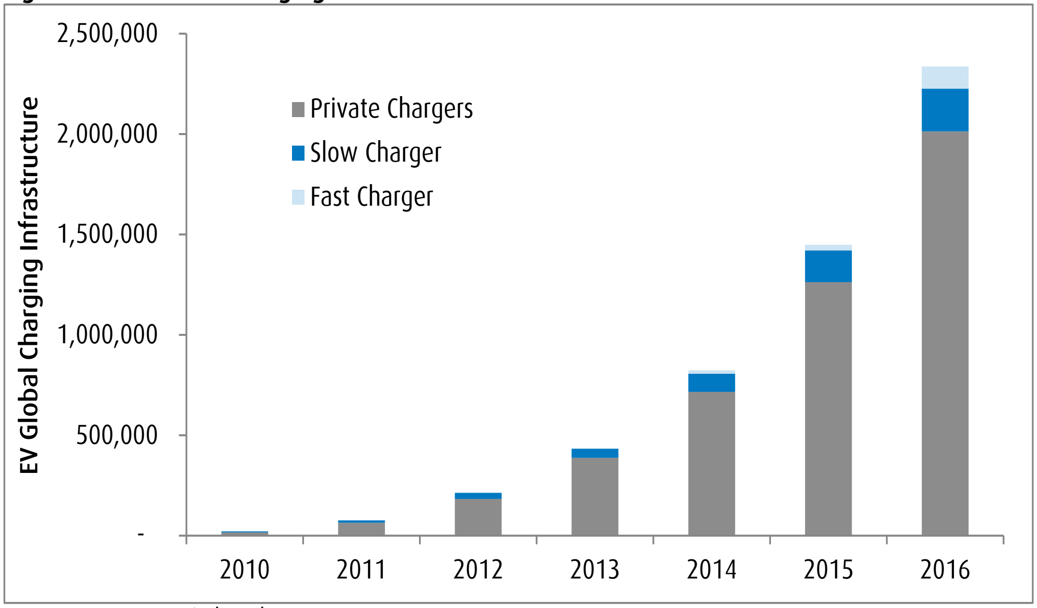
US06 – Is a Supplemental Federal Test Procedure (SFTP) that was developed tests the implications of aggressive, high speed and/or high acceleration driving behaviour, rapid speed fluctuations and driving behavior following start-up.

Source: National Renewable Energy Laboratory (NREL)

2. Charging Challenges – Another Impediment to Adoption

Charging behaviours and the amount of charging infrastructure available are also an important impediment to wide-scale EV adoption. **We believe that if charge times could be decreased to 10-15 minutes, then EV adoption would likely progress much faster because it would alleviate the range anxiety described earlier.** Right now, charging typically occurs overnight and for some, that is enough. However, for many others, the charging question would change the average day.

Figure 78: Bulk of EV Charging Done at Home



Source: IEA, BMO Capital Markets

EV owners currently have to wait much longer to charge their vehicle compared to filling up an ICE gas tank AND stop over more often because EV ranges are not comparable to ICE cars yet. Using public charging stations is currently limited and the costs are not cut and dried. It currently takes ~30-40 minutes (using a "fast charger") and can take hours with slower level 1 or 2 chargers to charge an EV. Fast chargers (~3C) can only be used to reach 80% capacity and some batteries cannot use them at all. Tesla cars can use any type of charger, but not every EV can use a Tesla supercharger or any other fast charger for that matter.

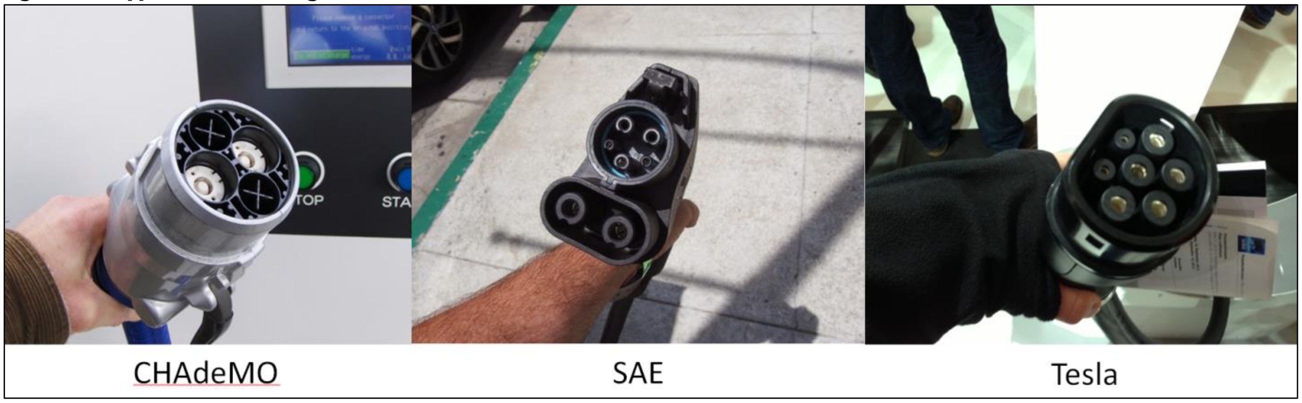
There are currently three main EV charger types. EV charge points are characterized by the power (kW) produced, equating to speed of charge.

- **Level 1C (Slow chargers: 120V/15 Amps)** The most common form of charging, typically overnight at home as full charge takes many hours with power delivery of up to 3kW.
- **Level 2C (Typical household chargers: 240V/30 Amps):** Can fully recharge EVs in ~1-4 hours with power delivery of 7-22kW (speeds will depend on the model's on-board charger). These chargers are typically found near shopping centres or supermarkets.
- **Level 3C (Fast Chargers: 480V/100 Amps):** Fast chargers can provide ~80% charge in ~30 minutes with varying power delivery (40- 120kW). They are typically found in locations close to highways and are the preferred charging stations for Tesla's vehicles.

Tesla's onboard computer will slow down the charging process if fast chargers are used too frequently

There are also different types of fast chargers (level 3C), which include CHAdeMO, SAE and Tesla's supercharger; the type of charger that can be used depends on the car type and availability of adapters. Tesla is currently the only car that can use all chargers because of its adapters while others may or may not be able to adapt to other charging designs. However, using a supercharger all the time degrades the battery and Tesla's onboard computer will slow the fast charging process if it is used too often.

Figure 79: Types of Fast Chargers Available



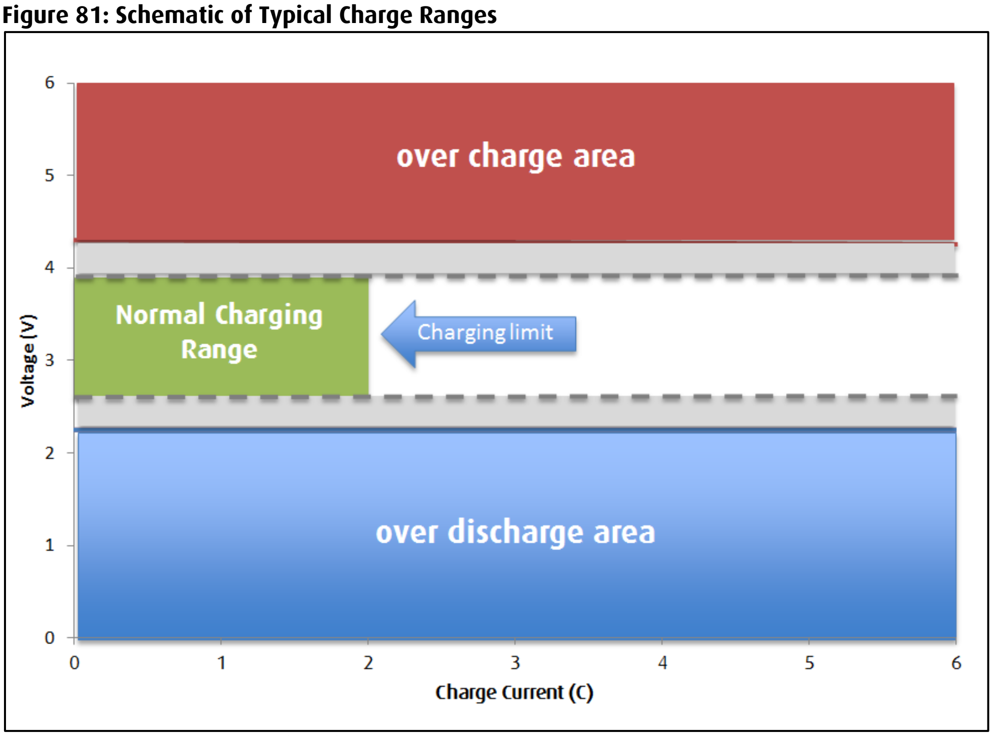
Source: Inside EVs, greentransportation.com

Charge Capacity Needs to be Maintained Within a Certain Range

As noted above, level 1 and level 2 charging levels do not have a recommended charge limit of 80% as with level 3 superchargers. Batteries are typically designed to operate within an acceptable charge range as "over charging" and "over discharging" tend to shorten the projected life span of the battery. However, the grey zones in Figure 81 are not bound by constant variables making this much more problematic to predict. While manufacturers have invested heavily in developing software to remove the guess work for drivers, it is impossible account for all the critical variables. From our previous discussion, we know that high voltage charging damages the anode, increases structural disordering of the cathode and causes cracking of the binder and the anode. Therefore, using a supercharger all the time will decrease battery life.

The limits between normal charging and the overcharge area (grey zone) is not cut and dried and ambiguity exists

Figure 81: Schematic of Typical Charge Ranges



Source: Bugga and Smart *et al.* (2014), BMO Capital Markets

Charging speeds will need to improve at the battery, charger and battery management system (BMS) levels. A first step would be to increase charging infrastructure and the ability of all battery chemistries to charge quickly in a bind without damaging the battery. Unless this occurs, this issue will remain a significant impediment to consumer uptake, in our view. As it stands, BEVs are fine for city driving in the course of a day's travel and charging overnight at home. But there are more complications as some multi-residence buildings may not permit private chargers.

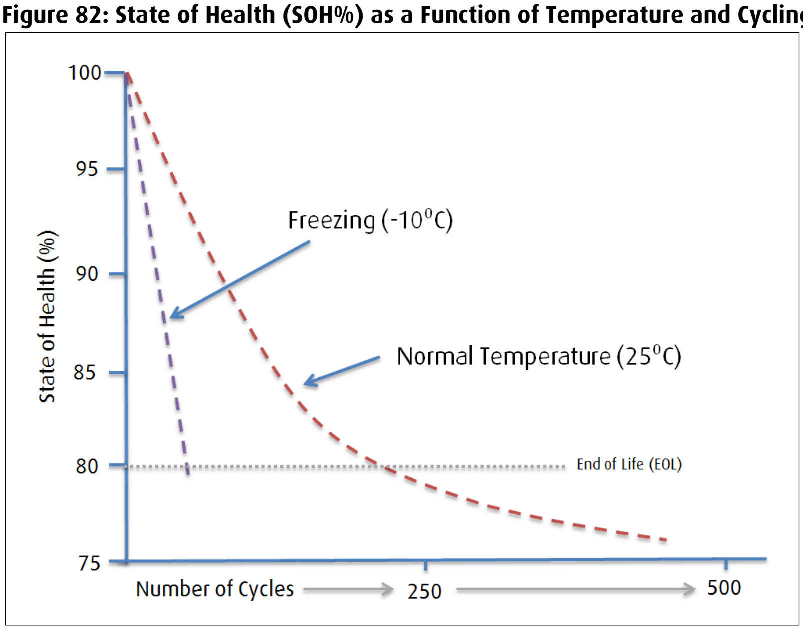
Variable costs on the road are also an issue as, according to fleetcarma.com, an EV driver would pay $10 for a 30-minute charge at an EVgo station in Santa Monica, which would provide only 65-80 miles in an e-Golf or a Nissan Leaf. In addition, finding a charging station can be difficult and current EV drivers would know the frustrations of finding a charge station only to discover it's crowded or out of order.

This all being said, global public charging infrastructure grew ~70% in 2016 and continues to rise quickly and battery designers are working to solve the charge time issue. However, there are also issues with charging in suboptimal temperatures, which also needs to be looked at more intensely.

Charging in Sub-Optimal Temperatures

Optimal ambient temperature for charging = 15°C to 49°C (60°F to 120°F). The outside temperature during the charging process is also a significant factor to consider. The optimal ambient temperature for charging rates is around 15°C to 49°C (60°F to 120°F) and outside of that range, there is increased resistance within the battery. As we have pointed out, charging any battery that contains manganese at high temperatures is particularly damaging. But while BEV drivers can certainly take precautions during the occasional heatwave, northern parts of the globe have much bigger problems when temperatures dip below the freezing mark. We discussed how the battery discharges faster in colder temperatures, but it also takes longer to charge and the battery degrades much faster despite lower voltage charging. Researchers have also shown that a low temperature during the charging process accelerates lithium plating — a hazardous mechanism that causes irreversible erosion and dendrite formation — a precursor to thermal runaway.

Figure 82: State of Health (SOH%) as a Function of Temperature and Cycling



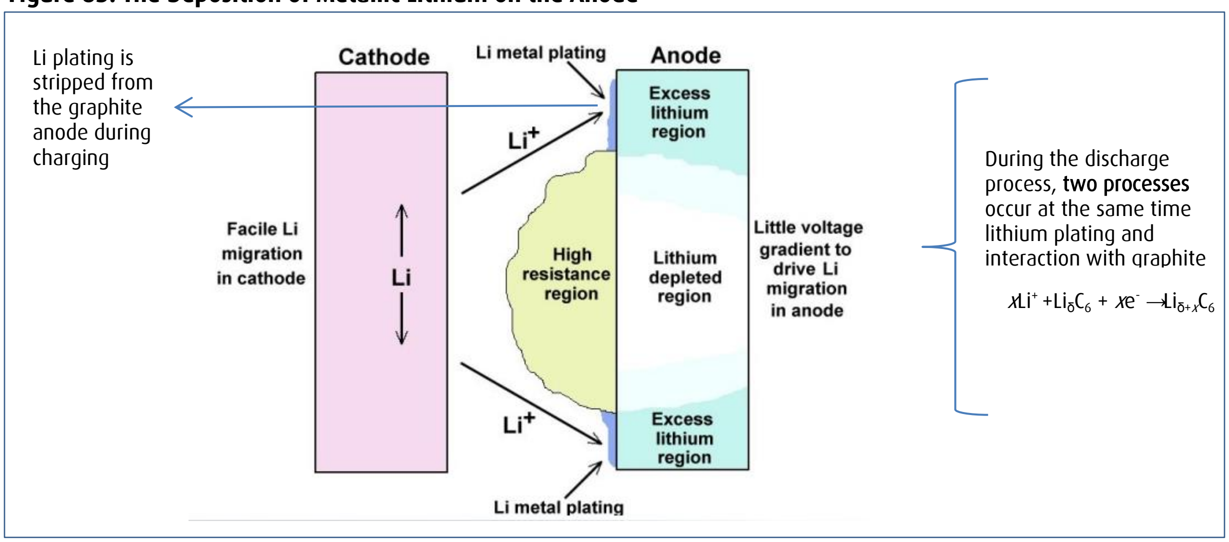
Source: Fleischhammer *et al.*, 2015, BMO Capital Markets

Lithium Plating Is a Precursor to Thermal Runaway

Charging in cold temperatures dominant cause of plating. Lithium plating involves the deposition of *metallic lithium* on the graphite anode during discharging and the subsequent 'stripping' during normal charging. One of the principal aging mechanisms is that as the battery is charged more and more, some of the plating remains on the anode thereby reducing the amount of active materials. This is usually taken into account when manufacturers estimate the end of life (EOL). However, this process is not as efficient during supercharging, overcharging and charging with a normal charger when the temperature drops. Charging in cold temperatures is the dominant cause of plating and the rate of deposition accelerates *as the temperature becomes increasingly negative*. This results in capacity loss because it interferes with the rate of lithium insertion at the anode and a loss of lithium dramatically decreases battery life.

Lithium plating is somewhat reversible. Fortunately, lithium plating is somewhat reversible as there is a 'stripping' mechanism at the beginning of the charging process (i.e. potentials of more than 100mV) that allows the metallic lithium deposited to oxidize. We use the term 'somewhat' here because it's not a solution as some deposits could remain even in normal circumstances. Therefore, scientists often talk about a loss of 'reversible lithium' — or the lithium that can be stripped from the anode after deposition — that causes capacity loss and poor efficiency. In addition to interfering with the anode, plated lithium can break off and float in the electrolyte (i.e. dead lithium). Therefore, while we know Li plating is highly correlated to charging conditions manufacturing defects also play a role. While ageing mechanisms such as this are part of the deal with LIBs, as more and more lithium deposits remain on the anode it could pave the way for dendrite growth.

Figure 83: The Deposition of Metallic Lithium on the Anode



Source: The Aerospace Corporation; BMO Capital Markets

A Little More Detail for the Scientifically Inclined

How Lithium Plating Quickly Becomes a Problem

During the charging process, Li-ions move from the cathode to the graphite anode and goes inside the graphite anode as there is a *positive polarization* between them at about 0.1V. This means that the battery is working normally and lithium plating is unlikely to occur. However, researchers found that as temperatures dip below freezing, *that polarization becomes increasingly negative.* This, coupled with the fact that the ion transport rate is quicker than the rate the anode can accept them (rate of intercalation), increases the likelihood of plating.

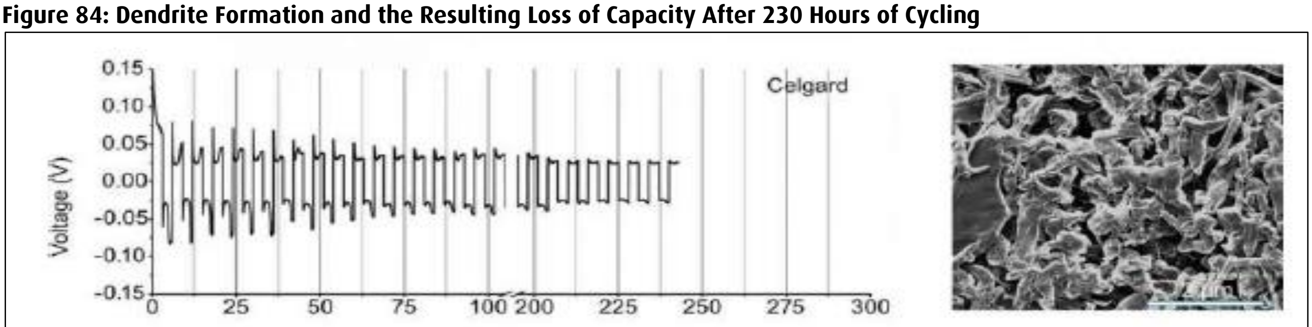
In colder temperatures, charging times increase, which also favours lithium plating. This is because there are competing processes present during charging — the intercalation charge and the plating charge. As the latter becomes dominant, there are fewer vacancy sites for Li intercalation, gradually reducing the charge current for this process paving the way for plating. As a consequence, lithium plating becomes more severe with charging time. Finally, once deposited, metallic lithium reacts spontaneously with the electrolyte forming a film that begins to consume both the active lithium and the electrolyte, and increasing internal resistance. Therefore, once deposition begins, the Li metal reacts with the electrolyte causing a reduction in that solution as well as the number of li-ions that are needed for normal operation.

Lithium Plating →Dendrite Formation → Thermal Runaway

For decades, dendrite formation has plagued the battery industry. Anecdotes of smart phones and laptops 'catching fire' can be mainly attributed to this phenomenon. However, despite extensive research, the mechanisms remain a mystery. We do know that lithium plating is a precursor to dendrite formation.

Dendrites are needle-like, microscopic fibers that form on the surface of the anode during the charging process. As dendrite formation continues on the anode and growth towards the cathode begins, capacity loss within the battery becomes more pronounced.

Figure 84: Dendrite Formation and the Resulting Loss of Capacity After 230 Hours of Cycling

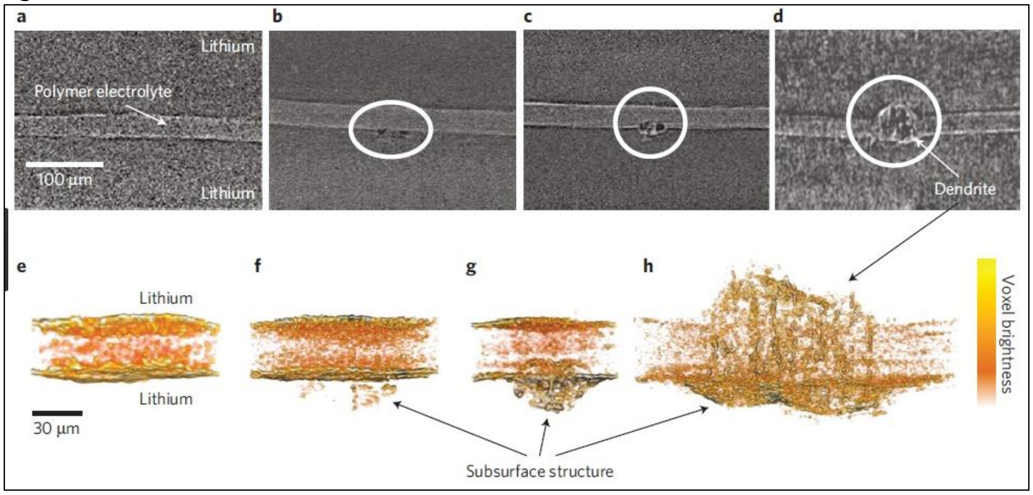


Reprinted with permission from Hao *et al.* (2016). DOI: 10.1021/acs.nanolett.5b05133

As the battery experiences more charging cycles (lithium plating) there is an increasing possibility of dendrite formation. Once a critical mass is obtained, they spread across the battery until they reach the cathode. As the dendrites pierce the separator, the battery experiences multiple short-circuits that will eventually lead to what industry insiders call "catastrophic failure" of the battery.

Essentially, dendrite formation is a root cause of low efficiency, low cycling performance, short circuiting, and thermal runaway.

Figure 85: Dendrite Movement From One Electrode to Another



Source: Phys.org

Solutions to Lithium Plating:

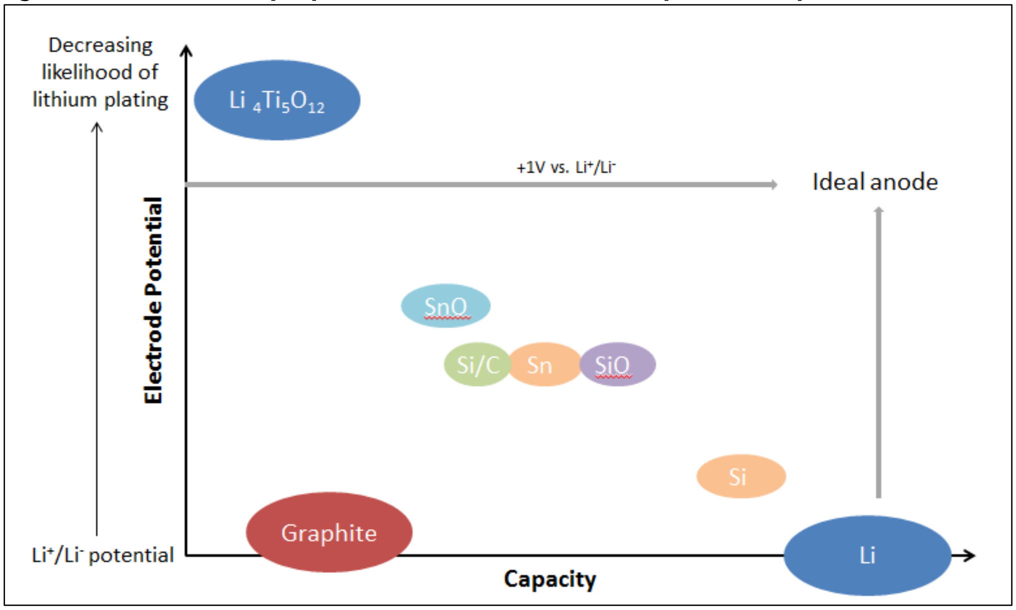
i. Improving Battery Design

While the mechanisms are not completely understood, battery designers have come a long way in curbing the likelihood of lithium plating. For example, making the anode 1mm longer than the cathode, increasing the thickness of the cathode compared to the anode, increasing separator thickness, and increasing the anode to cathode ratio (A/C) ratio or decreasing the cathode to anode ratio (C/A), could delay or even halt formation. But doing so reduces capacity, and balancing this ratio, and keeping it, continues to be a problem. Preventing anode degradation remains elusive and as it degrades, the cell becomes unbalanced and the capacity of the cathode outweighs that of the anode leading to an increased rate of plating. Therefore the principal solution to the lithium plating problem is to change the anode materials.

ii. In Search of the Optimal Anode Material

Graphite may be the gold standard anode material in commercialized batteries, but it is more susceptible than other materials to lithium plating, as its electrode potential, as seen in Figure 86 is very similar to that of metallic lithium. Therefore, changing the anode composition to something that has a very different potential than that of lithium would be beneficial, but it is easier said than done. Again, changing the chemistry causes other issues. For example, the safer lithium titanate ($Li_4Ti_5O_{12}$) may not be susceptible to lithium plating, but the high cost of titanium and the reduction in capacity means that it is not a suitable replacement even though it is in some models.

Figure 86: Lithium Battery Experimental Anode Materials Compared to Graphite



Source: Sanyo; BMO Capital Markets

A Little More Detail for the Scientifically Inclined

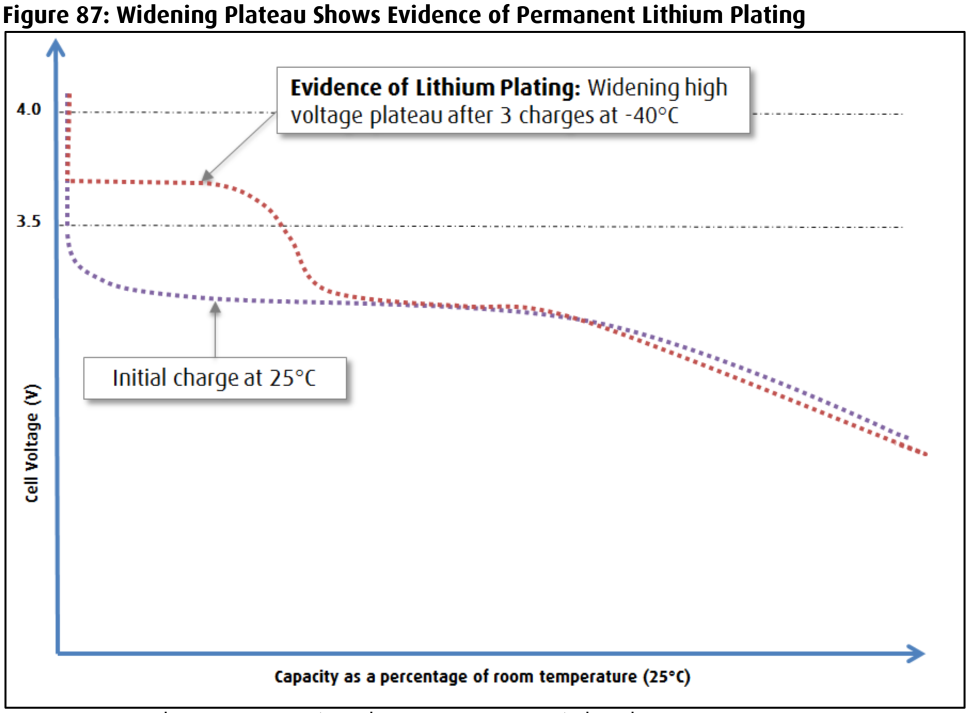
Why Does the Graphite Anode Promote Lithium Plating?

Graphite may be widely used in commercialized batteries, but it is more susceptible than other materials to lithium plating as its potential is close to that of metallic lithium or operates at ~0.1V versus Li^+/Li^-. Therefore, changing the anode composition to something that has a very different potential than that of lithium would be beneficial, but it is easier said than done. Alternatives such as silicon (Si) or tin (Sn) also have similar potential profiles and therefore, would have the same lithium plating issues. The use of lithium titanates ($Li_4Ti_5O_{12}$) offers a solution as its potential to lithium is much more positive at ~1.6V versus Li^+/Li^-. However, its capacity is lower than that of graphite and its cost is much higher. Suffice it to say that the search is on for the ideal anode that has a potential of **more than 1.0V versus Li^+/Li^-** that also does not compromise capacity nor increase cost.

iii. Applying Adequate Charging Protocols

The easiest way to prevent lithium plating is to avoid charging over 4.2 volts per cell and avoid charging the vehicle at temperatures below -10°C -to-15°C. Researchers out of Oxford University found that these temperatures pushed the anode potential below 0v at every step. In addition, using superchargers when the battery is at a high state of charge (>80%) should also be avoided. To reduce end-user errors, the researchers at the ZSW institute proposed a "step wise" charging strategy, where there is a high rate of charging at the beginning to facilitate the "stripping" mechanism followed by a low rate charge. However, this would require the introduction of a reference anode into the design.

Figure 87: Widening Plateau Shows Evidence of Permanent Lithium Plating



Source: Bugga and Smart, 2010, Hein and Latz, 2015, BMO Capital Markets

iv. Preheating the Battery

This has long been recommended by scientists, but homogenous execution has been difficult. This is a direct result of the different battery management systems employed.

v. Developing Detection Systems

Detection systems are still evolving and most battery management systems employ an electrochemical technique that involves detecting the different behaviours of deposited lithium and reversible lithium. These include measuring discharge voltage, increase in anode resistance, increase in anode over-potential, and changes in electrolyte polarization in cell.

1. Other possibilities include measuring anode potential to see if it is negative. But this would involve employing a reference anode, which can be quite tricky. For example, the built-in reference anode can interfere with the electrochemical processes.

2. Another detection method includes measuring coulombic efficiency or the ratio of discharge to charge capacity. However, there are other side reactions that could also account for lower rates.

3. Measuring the width of the high voltage plateau or the ‘stripping discharge’. As the stripping reaction becomes less efficient, the voltage ‘plateau’ that occurs at the beginning of the charge cycle becomes wider.

Battleground #3 – Race to Reduce Range Anxiety

Improving Battery Management Systems

The battery management systems (BMS) are essentially ‘the brains’ behind the battery as it ensures that the battery does not get overheated, prevents cell unbalancing and ensures safe and reliable operation. Again, OEMs employ a number of different battery management systems either developed internally or sourced, with the main goals being to prevent thermal runaway and manage the state of health (SOH) of the battery. An optimal BMS should be designed to maintain a temperature difference of about 5°C between cells and have accurate state of charge (SOC) levels to avoid overcharging or discharging. However, since lithium ion batteries are so fussy, battery management systems are complex and getting the software wrong can lead to a number of complications. For example, the production delays of Tesla’s Model 3 are largely due to re-writing all the software.

The company that can produce a BMS that can limit degradation, accurately assess the state-of-charge and prevent thermal runaway in a safe and reliable manner will have the competitive edge. Similar to battery design, many OEMs also have BMS units. There are not that many pure plays in the BMS space although there are many start-ups that are worth watching.

Figure 88: BMS Companies Are Mostly Private Engineering Firms

	Country	Exchange	Symbol	Commentary
123 Electric	Netherlands	Private		Focused on BMS for LFP batteries
Analog Devices, Inc.	**U.S.**	**NASDAQ**	**ADI**	**Chip vendor for BMS systems**
Aptiv PLC	**UK**	**NYSE**	**DLPH**	**Auto parts technology company that includes a BMS system**
Amperex Technology Limited (ATL)	China	Private		A battery supplier with a BMS unit
BAIC Group	China	Private		OEM with a battery and BMS unit
Bejing Pride New Energy Battery Technology Co., Ltd.	China	Private		BMS units for LFP
BorgWarner Inc.	**U.S.**	**NYSE**	**BWA**	**Cabin heater extender to increase driving range in cold temperatures**
Bosch	Germany	Private		Thermal management under the Mobility Solutions unit
Buhler Motor	Germany	Private		Auto parts with thermal management options for Evs
BYD Co., Ltd.	**China**	**SHE**	**2594**	**BMS unit for LFP for its own use**
Calsonic Kansei Corporation	**Japan**	**TYO**	**7248**	**Electronic autoparts including BMS systems**
China Aviation Lithium Battery Co., Ltd. (CALB)	China	Private		BMS for its LFP batteries for EVs & locomotive applications
CIE Solutions	U.S.	Private		Custom batteries and BMS systems
Clayton Power	Denmark	Private		Lithium ion battery company with integrated BMS
Denso Corporation	**Japan**	**TYO**	**6902**	**BMS systems for Mazda and Toyota**
Digi-Triumph Technology	Taiwan	Private		Ni-Mh producer and BMS for lithium ion batteries
Eberspacher Vecture Inc.	Canada	Private		BMS systems for LCO, LMO, NMC and LFP
Elite Power Solutions	U.S.	Private		BMS for large scale LFP applications
Elithion, Inc.	U.S.	Private		BMS for stationary battery installations
Ewert Energy Systems	U.S.	Private		BMS for PHEV and BEVs
FEV Europe GmBH	Germany	Private		Engineering services for the autoindustry - mainly software applications
Gbatteries Energy	Canada	Private		Received $1.2M in funding from the Canadian Government
Hefei Guoxan High-Tech Power Energy Co., Ltd.	**China**	**SHE**	**2074**	**Subsidiary of Guoxan High Tech Co. Ltd - a Chinese OEM**
Hella KGaA Hueck & Co.	**Germany**	**ETR**	**HLE**	**Auto electronic parts that includes a BMS system**
Hitachi Automotive Systems, Ltd.	**Japan**	**TYO**	**6501**	**Subsidiary of Hitachi, Ltd.**
Huizhou Epower Electronic Co. Ltd.	**China**	Private		**Subsidiary of Zhongmei Machinery Group Co., Ltd.**
Hyundai Kefico	**South Korea**	**KRX**	**5380**	**Electric Vehicle Power Control Units and BMS for PHEVs**
Infineon Technologies AG	**Germany**	**FWB**	**IFX**	**Chip Vendor for PHEV and Evs**
LG Innotek	**Korea**	**KRX**	**11070**	**BMS subsidiary of LG Electronics**
Anhui Ligoo New Energy Technology Co., Ltd.	China	Private		R&D for electronic control systems
Lion Smart GmbH	Germany	Private		Engineering Service company with a BMS unit
Lithium Balance	Denmark	Private		BMS and other EV accessories such as chargers
Magna International Inc.	**Canada**	**TSE**	**MG**	**Autopoarts with a wide variety of EV components**
Mahle GmbH	Germany	Private		Auto parts with a thermal management component
Mitsubishi Electric Corporation	**Japan**	**TO**	**6503**	**Electric autoparts that include BMS systems**
Nidec Corporation	**Japan**	**TYO**	**6594**	**Builds motors for electric cars**
Preh GmbH	Germany	Private		Automotive electronic solutions including a BMS system
REAPsystems Ltd.	U.K.	Private		BMS for E-bus and marine applications
Renesas Electronics Corporation	**Japan**	**TYO**	**6723**	**Semi-conductor company with a BMS subsidiary**
Rheinmetall AG	**Germany**	**FWB**	**RHM**	**Provides an electric coolant pump for Evs throughs its Pierburg subsidiary**
Rimac Automobili	Croatia	Private		Electric drivetrains and battery systems
Shaeffler AG	**Germany**	**FWB**	**SHA**	**Auto parts with a thermal management component**
Sunwoda Electronic Co., Ltd.	**China**	**SHE**	**300207**	**BMS systems for IT applications**
Tesla Motors	**U.S.**	**NASDAQ**	**TSLA**	**OEM with its own BMS unit**
Texas Instruments	**U.S.**	**NASDAQ**	**TXN**	**BMS systems for EV and PHEVS**
The Eberspacher Group	**Germany**	**ENX**	**FR**	**High Voltage Coolant Heaters**
Valeo	France	Private		An EV company with a thermal management systems group
Voltronix USA, Inc	U.S.	Private		Main applications are for RVs, ATVs and Marine
Voss Automotive GmbH	Germany	Private		Auto parts with a thermal management component

Source: BMO Capital Markets

Increasing Charging Infrastructure

Charging infrastructure is often cited as a key factor in reducing range anxiety and we agree that it is a major hurdle. As vehicle range improves, there is still the added nervousness about using a pure electric car for long haul travel. Having a charging infrastructure that is as ubiquitous as a gas station would certainly help EV adoption rates. Tesla understood this from the beginning and recently announced an expansion of its supercharging network – especially in urban centres.

In Europe, energy companies have been acquiring charging companies. In 2017, Engie SA acquired EVBox, a charging company with 40,000 charging points and Shell acquired NewMotion, which has 30,000 charging points. As the vehicle market shifts, it seems clear that traditional energy companies are trying to ensure retail locations benefit from the growing EV market. Furthermore, Italy's Enel S.p.A., through its U.S. subsidiary EnerNOC, acquired California's eMotorWerks to take advantage of the expanding charging infrastructure in North America. Utilities are also making substantial investments in charging infrastructure. For example, San Diego Gas & Electric is currently building an infrastructure of 3,500 chargers at a cost of $45 million.

While the EV charging sector appears to be changing rapidly, the differences in the charging heads and different payment methods have made it difficult for consumers. In China, for example, the government formed the State Grid Corporation of China (SGCC), which cooperated with 17 EV charging networks to build the world's largest charging infrastructure, which has 167,000 stations. The problem is that many customers have complained that the charging stations are not uniform, are complicated to use, have different payment methods with complicated apps and are often not in service. The reality is that increasing charging infrastructure in North America and Europe needs to be uniform and the company that is compatible with the greatest number of models will likely win.

Figure 89: Not Many Pure Plays in the Charging Space

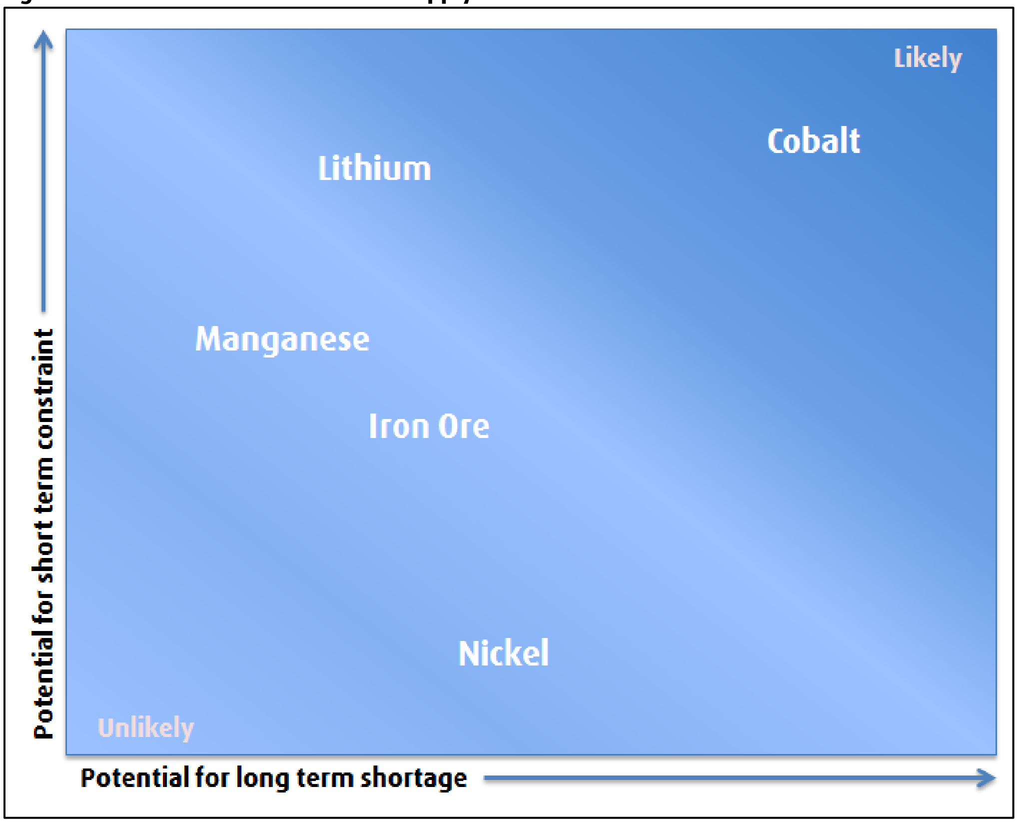
Charging Station Equipment	Country	Exchange	Symbol	Commentary
AeroVionment, Inc.	U.S.	NASDAQ	AVAV	EV charging system partnership with Volvo, Nissan and Ford
Blink Charging Co.	U.S.	OTCMkts	CCGI	Operates tnetwork of 40,000 2C and 3C chargers
EV-Box	Netherlands	EPA	ENGI	Largest charging company in EU; Subsidiary of Engie S.A.
Envision Solar	U.S.	OTCMkts	EVSI	Solar accessories for charging stations; agreement with ChargePoint, Inc.
Fortum Oyj	Finland	NASDAQ:N	FORTUM	Energy company setting up a charging network in the baltic states.
GE	U.S.	NYSE	GE	Level 2 indoor/outdoor charger and public charging options
NewMotion	Netherlands	AMS	RDSA	Acquired in October 2017 by Shell
Siemens AG	Germany	ETR	SIE	Versicharge line of flexible charging systems
Tesla, Inc.	U.S.	NASDAQ	TSLA	Proprietary charging network for its customers
Allego	Netherlands	Private		Implemented the first public fast chargers in EU
Bosch GmbH	Germany	Private		Multiple product lines that include home charging systems
ChargePoint, Inc.	U.S.	Private		Focused on aggregating local charging stations
ClipperCreek, Inc.	U.S.	Private		Level 2 commercial and residential portable chargers
EV-Go	U.S.	Private		Largest network of fast chargers in the U.S.; recently sold by NRG Energy, Inc.
EVoCharge	U.S.	Private		Mostly on the West Coast
Electric Motor Werk, Inc.	U.S.	Private		Smart charging system called JuiceNet; acquired by EnerNOC
FLO Inc.	Canada	Private		Canada's largest EV charging network
Leviton Manufacturing Co., Inc.	U.S.	Private		Electrical device company that also produces home and commercial charging stations
SemaConnect	U.S.	Private		Installed 150 stations in the D.C. area; SAE Level 2 chargers
Sun Country Highway	Canada	Private		Level 2 charging that includes portable charging device
Ubitricity	Germany	Private		Specializes in streetlight car charging ports

Source: BMO Capital Markets

Part V – The Supply and Demand of Key Raw Materials

Bottom Line: The lithium ion battery industry is preparing for massive growth. We believe that a 1% penetration by EVs in the global car industry represents a significant shift in the supply chains of battery raw materials. This is an important consideration since materials need to be qualified four to five years ahead of car launches. This means that supply chains of key materials such as lithium, nickel and cobalt will have a significant impact on projected EV market penetration rates. Battery manufacturers have and will continue to design batteries based on the cost and availability of key commodities.

Figure 90: Possibilities of Short-Term Supply Constraints



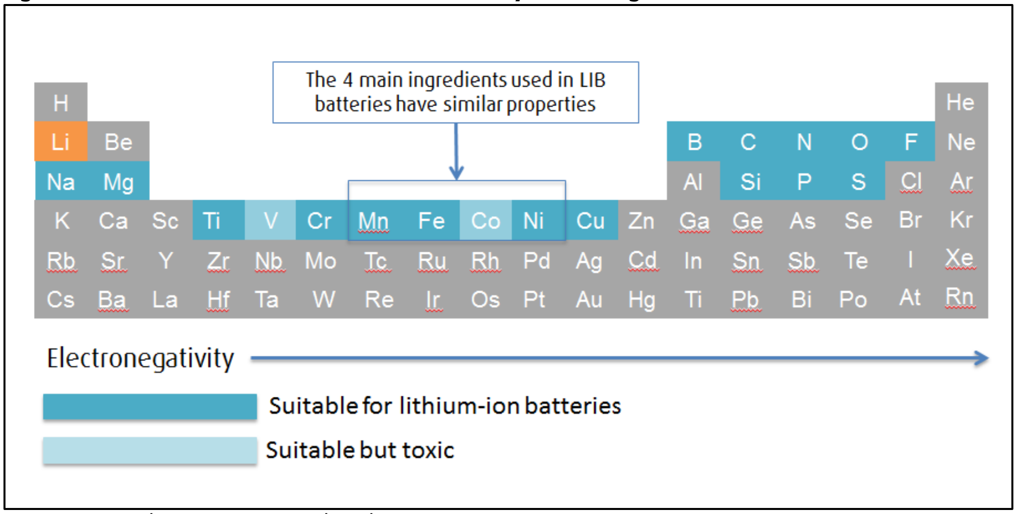
Source: BMO Capital Markets

The different types of lithium batteries are named after the principal materials in the cathode. Figure 91 shows the elements that are considered suitable for the cathode (turquoise) and those that are not suitable (grey) for a variety of reasons. While there are a number of possibilities we are going to focus our analysis on the demand and supply of the elements currently used in commercialized lithium batteries today. We believe that lithium, cobalt and nickel have supply constraints that could cause significant delays and increase overall costs.

We believe that it is not easy to substitute these elements or replace them with another that would not have the same supply issues. Therefore, this is another reason why the trend has been to improve the current chemistries from a capacity, safety, and cost perspective.

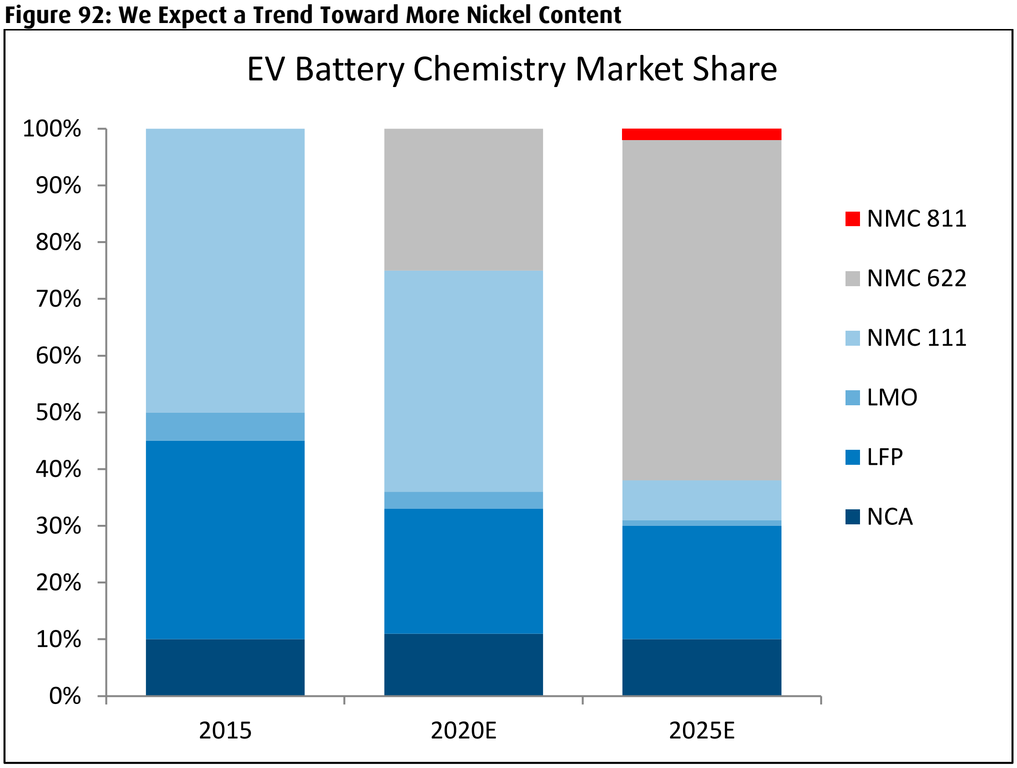
Ni, Co, Fe and Mn share similar properties, but cobalt is also toxic

Figure 91: Elements That Are Suitable for Battery Technologies



Source: Liu *et al.*, 2016, BMO Capital Markets

Figure 92: We Expect a Trend Toward More Nickel Content



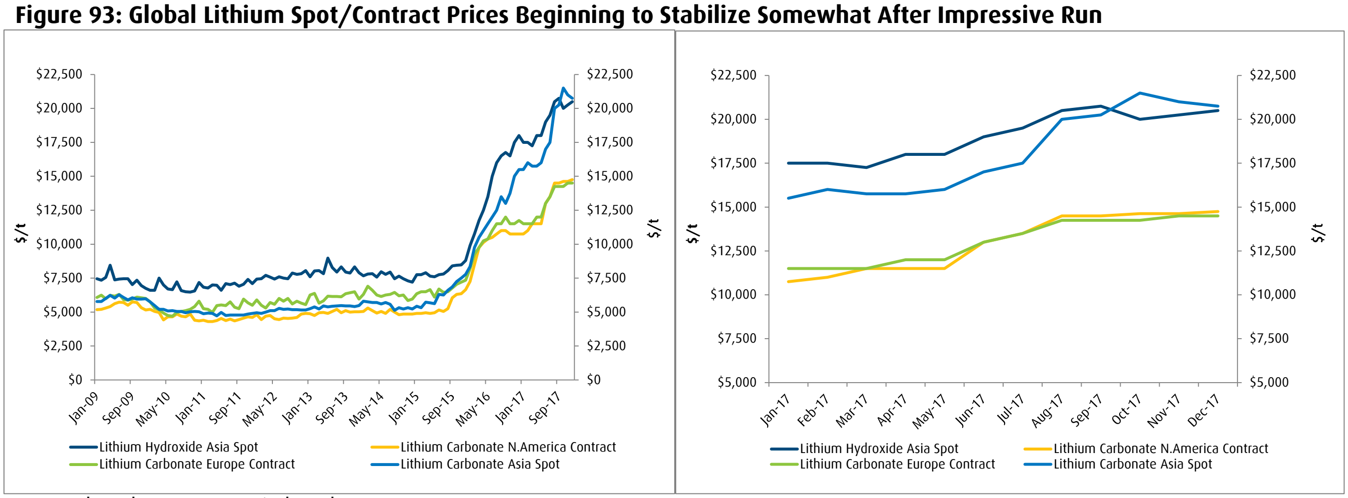
Source: BMO Capital Markets

1. Lithium: Strong Demand Led by EV Momentum, But Supply Response Looms

Bottom Line: Lithium demand is growing at a fast pace as the EV transition accelerates, but a significant supply response looms, likely overwhelming the large (but not as large) demand growth trajectory by 2019. We still expect realized lithium prices to trade up some more in 2018, averaging ~$14k/t LCE (lithium carbonate equivalent) versus spot ~$13-14k/t, before starting to fall back in 2019 and stabilizing at ~$10k/t. We do expect the battery supply chain to remain anxious regarding EV metals, and so we don't expect lithium to fall to the cost curve (below $10k/t).

While lithium has relatively smaller demand than other commodities (~210-225kt currently), its oligopolistic supplier base, added to the highly secretive nature of the battery industry, renders lithium a difficult, and arguably opaque, industry to operate in and follow. Although it is a relatively common geological commodity with production predominantly out of Chile, Argentina and Australia, the relative opacity of lithium even makes following lithium-related prices difficult, as spot prices may be citing tiny, one-off transactions (handfuls of tonnes), while much lower contract prices are the metrics at which the large, well-followed public equities are transacting.

Figure 93: Global Lithium Spot/Contract Prices Beginning to Stabilize Somewhat After Impressive Run

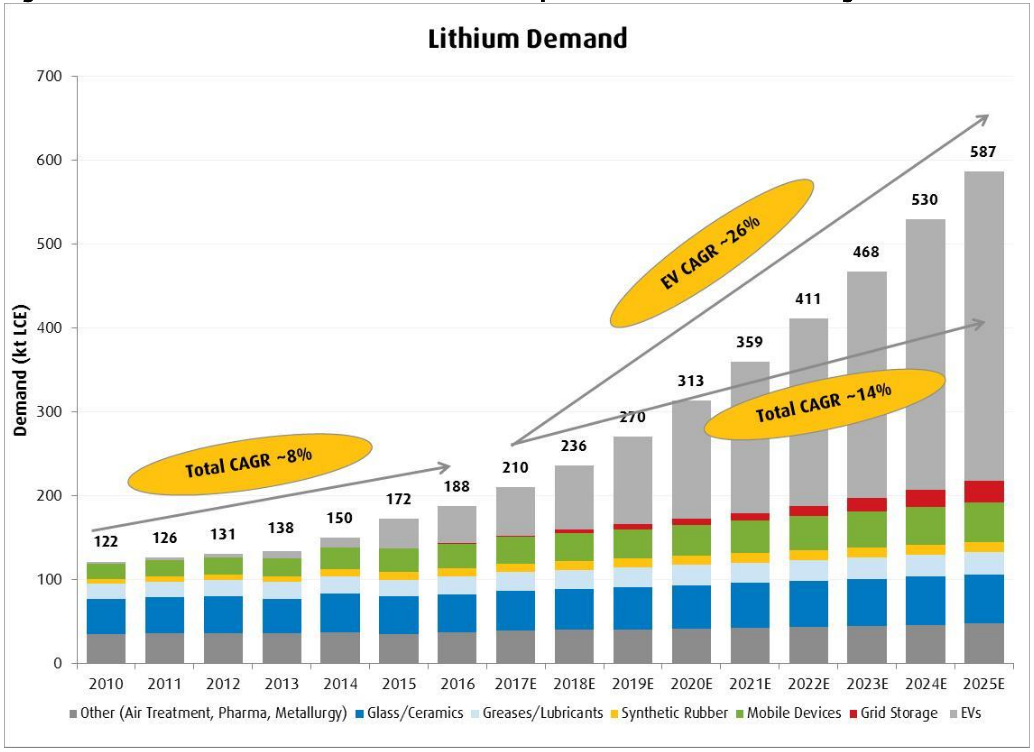


Source: Bloomberg, BMO Capital Markets

DEMAND: EV Momentum Underpins Significant Lithium Demand Growth

Lithium demand growth is being led by the accelerating EV market, underpinning a torrid ~14% estimated CAGR to ~590kt LCE by 2025. Unlike other commodities discussed in this report, lithium is used in all batteries whether it is for EVs, mobile storage (cell phones, laptops, tablets, etc.) or grid storage. Lithium is also used in greases and lubricants and synthetic rubbers (tires, plastics, cookware, etc.), all with GDP-like growth. Lithium demand (inclusive of all products/compounds, i.e., carbonate, hydroxide, etc.) averaged ~8% growth for the decade pre-2016, but is now running at an expected 14% CAGR in our base case over the mid-term on the rapid technology push toward EV globally. Although batteries represented only ~15% of lithium demand in 2010, they now comprise ~40%, with the aggregate component of demand growing to 75% of the total mix by 2025, a 22% CAGR. As part of this, EV-related demand is expected to grow at a 28% CAGR through 2025, and we model EV-related sales rising to ~65% of total lithium demand in 2025 from ~25% currently.

Figure 94: Lithium Demand Grew at 8% CAGR & Expected to Grow at 14% Going Forward



Source: Industry Reports, BMO Capital Markets

SUPPLY: Meaningful Supply Response Coming to Abate Recent Shortfalls

We see the supply of lithium, a geographically common commodity, growing at a ~16% CAGR to ~780kt by 2025 as producers race to close the gap with demand that has outstripped supply in recent years. We expect the current supply shortfalls to abate in 2019 or 2020, but it is possible this could happen in H2/18 if new capacity ramps quicker than expected. However, lithium supply could still remain tight if expected EV penetration rates accelerate quicker or supply additions lag more than we predicted.

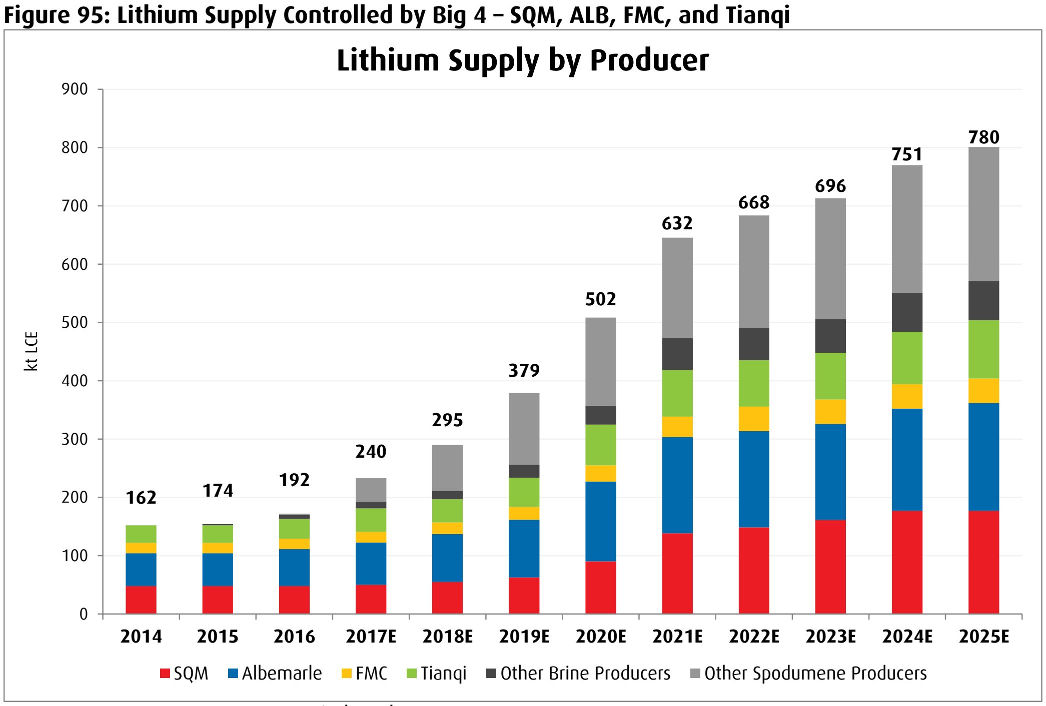
As a result of the recent supply shortage/uncertainty, we believe that lithium converters, and battery and cathode producers, have become anxious on ramping up purchases of lithium content (carbonate, hydroxide, spodumene, etc.), and locking in ownership, contracts and offtakes of current and future supply of lithium raw materials as the EV food chain begins to rev up, and industry participants all along the food chain (cathode producers → battery makers → automobile OEMs) jockey for first mover advantages and future market share.

Three-quarters of global lithium supply comes from four companies (SQM, Albemarle, Tianqi, and FMC), which are roughly split between brine mines (largely in Chile/Argentina) and open pit hard rock spodumene mines (in Western Australia). However, the supply base is quietly widening with new mines coming on.

- In Chile (SQM and ALB) and Argentina (FMC and upstart producer Orocobre), producers extract/pump lithium salts from subsurface brines (salars) up to dozens of metres below the surface, and concentrate them in elaborate surface evaporation pond networks, leading to harvests of lithium salt (as well as potash, boron and magnesium). These lithium salts (chlorides) are then processed into lithium carbonate and lithium hydroxide, key lithium sales products. Producing lithium from brine is complicated, and stems from the fact that underground brines are dynamic and pond networks interact with solar evaporation and wind cycles. However, brine mines are lower cost than spodumene mines and the end result typically does not need to be upgraded further to be battery grade (~99.5% Li_2CO_3/ lithium carbonate, though some production can be a little less than 99.5% Li_2CO_3 and customers may still buy it).

- On the spodumene side, about half of current lithium production stems from Western Australian open-pit mines that extract spodumene and then concentrate the ore via beneficiation (dense media separation, flotation, etc.). The end concentrate is then sold to converters (essentially in China) to further upgrade the raw concentrate to carbonate and hydroxide end lithium applications (7.5-8 tonnes of acceptable spodumene concentrate are typically required for one tonne of lithium carbonate or hydroxide). Talison (JV between Tianqi and ALB) is the largest spodumene producer but others have started ramping up (assisted with financing from various Asian battery supply chain off-takers/investors, etc.) as lithium demand/prices have risen. Spodumene is typically higher cost (and likely is setting the marginal prices of hydroxide and carbonate currently), though spodumene mines seem to be constructed at lower capex than brine and with shorter construction periods.

Figure 95: Lithium Supply Controlled by Big 4 – SQM, ALB, FMC, and Tianqi



Source: Company Reports, BMO Capital Markets

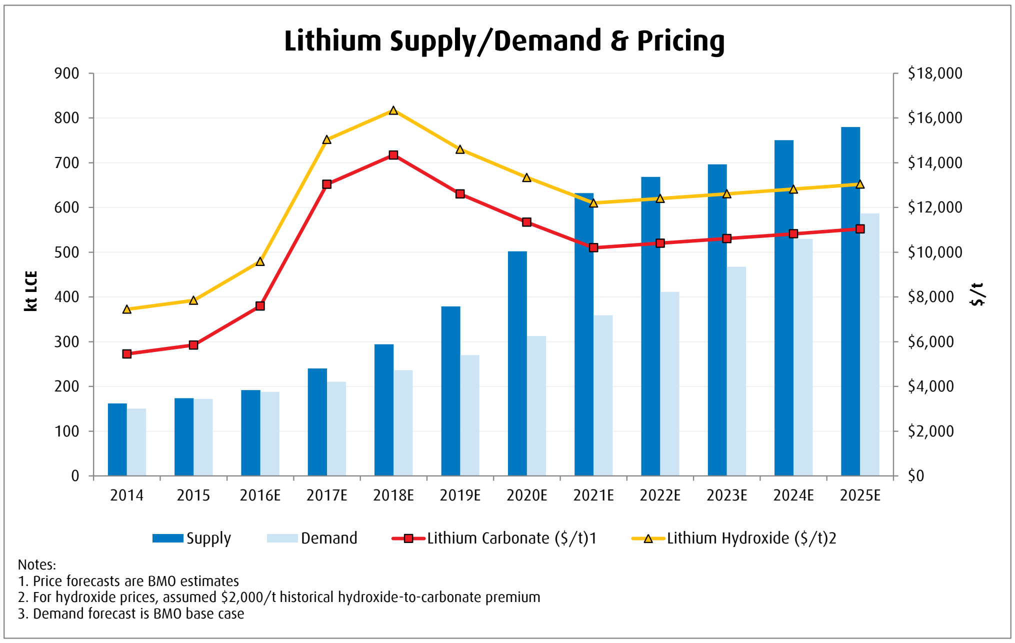
PRICE OUTLOOK: Lithium Prices to Rise Further Before Falling in 2019-2021

We expect lithium prices to rise further over the next year before falling back slightly as the current supply shortfalls abate. Under our base assumptions (i.e., 10% EV penetration by 2025), we model blended realized lithium carbonate/hydroxide prices rising a little in 2018 from the current ~$13-14k/t for large volumes (with hydroxide trading at premiums to carbonate) before falling in 2019-2021 and stabilizing at ~$10k/t LCE in 2021.

Our 2021 estimate is roughly the high end of costs for higher-cost Chinese capacity; however, we expect prices will not fall this low as demand growth will remain robust and there are always production issues (geological, weather, technical, etc.) at different mines from year to year that keep effective operating rates lower than potential. It just seems unreasonable to us that prices could stay at current high levels indefinitely.

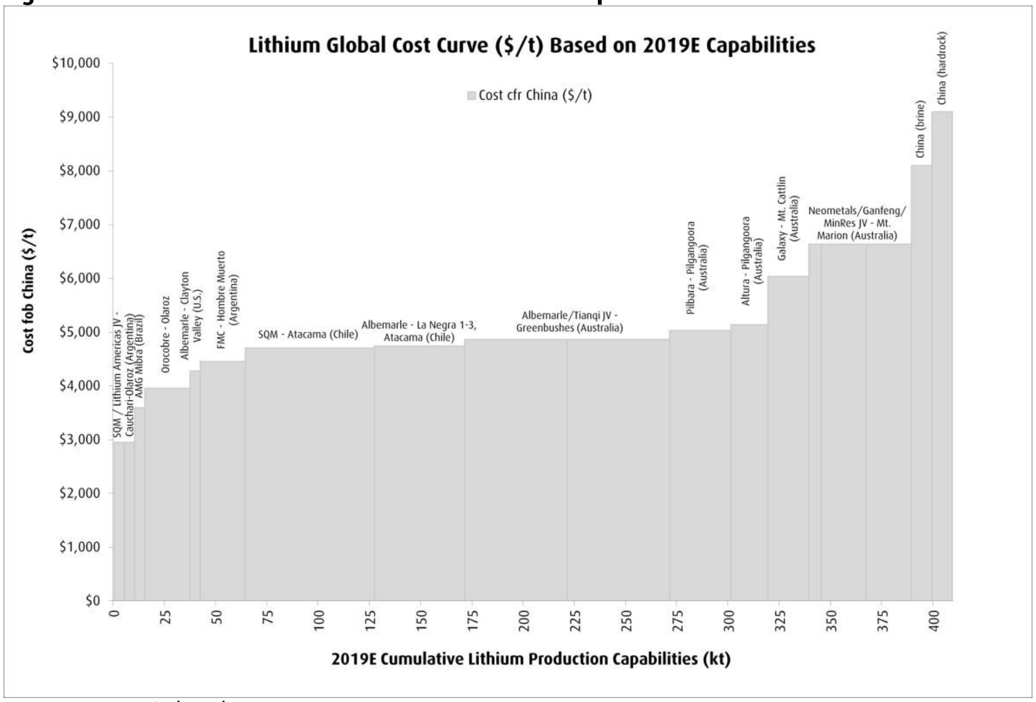
Lithium price discovery has been tricky so far in 2018. Chinese data points have suggested that prices have already begun to cool off (perhaps seasonal), which is contradictory to major producer guidance, implying 5-10% realized price increases for the year. With that said, tracking an average lithium price is difficult. First, carbonate/hydroxide are relatively illiquid commodities in which there are many spot/contract lithium price benchmarks to follow, but details around actual prices being realized under contracts and spot are opaque. Second, some spot sales of lithium carbonate are made well above $20k/t but these are tiny deals, likely not made by the large producers like SQM, Albemarle and FMC Lithium.

Figure 96: BMO Expects Lithium Prices to Rise Before Falling Back to Still-High Levels as Current Shortfalls Abate



Source: BMO Capital Markets, Industry Reports

Figure 97: Lithium Global Cost Curve Based on 2019E Capabilities



Source: BMO Capital Markets, Company Reports

For more on our current lithium outlook, please read the concurrent report *Lithium Puts and Takes So Far in 2018*, published by Joel Jackson on February 20, 2018.

Figure 98: Torrid Lithium Demand, But Also Supply Growth on Tap; Base Case 10% EV Penetration by 2025

kt LCE (lithium carbonate equivalent)		2014	2015	2016	2017E	2018E	2019E	2020E	2021E	2022E	2023E	2024E	2025E
Key EV Assumptions:													
EV Market Penetration Rate (BEV/PHEV of total car sales)		0.5%	0.6%	0.8%	1.2%	1.8%	2.7%	3.9%	5.1%	6.3%	7.6%	8.9%	10.0%
EV Car Sales (millions)		0.4	0.5	0.8	1.2	1.8	2.6	3.9	5.1	6.6	8.0	9.6	11.0
BEV (Battery Electric Vehicle)		*0.2*	*0.3*	*0.5*	*0.7*	*1.1*	*1.6*	*2.3*	*3.1*	*3.9*	*4.8*	*5.8*	*6.6*
PHEV (Plug-in Hybrid Vehicle)		*0.2*	*0.2*	*0.3*	*0.5*	*0.7*	*1.1*	*1.5*	*2.1*	*2.6*	*3.2*	*3.9*	*4.4*
EV Car LCE Content (kg/per kWh)		0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
BEV Avg. Battery Pack Size (kWh)		41.0	41.0	41.0	41.0	41.5	42.0	42.5	43.0	43.5	44.0	44.5	45.0
PHEV Avg. Battery Pack Size (kWh)		10.2	10.2	10.2	10.2	10.3	10.4	10.5	10.6	10.7	10.8	10.9	11.0
E-Bus Sales (millions)		0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
E-Bus LCE Content (kg/per kWh)		0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
E-Bus Avg. Battery Pack Size (kWh)		300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
Lithium Demand (kt LCE):													
EVs		12	35	44	58	77	104	141	180	224	271	322	368
Carbonate		*12*	*33*	*42*	*52*	*65*	*83*	*106*	*126*	*146*	*176*	*193*	*221*
Hydroxide		*1*	*2*	*2*	*6*	*12*	*21*	*35*	*54*	*78*	*95*	*129*	*147*
Glass/Ceramics		46	45	46	48	49	50	52	53	54	56	57	58
Greases/Lubricants		21	20	21	22	23	23	24	24	25	26	26	27
Synthetic Rubber		8	9	10	10	10	11	11	11	11	12	12	12
Mobile Devices		26	28	29	32	34	35	37	39	41	43	45	47
Grid Storage		0	0	1	2	4	6	7	9	12	16	21	26
Other (Air Treatment, Pharma, Metallurgy)		37	35	37	39	40	41	42	43	44	45	46	48
Total Demand		**150**	**172**	**188**	**210**	**236**	**270**	**313**	**359**	**411**	**468**	**530**	**587**
Demand Growth y/y			*14%*	*9%*	*12%*	*12%*	*14%*	*16%*	*15%*	*15%*	*14%*	*13%*	*11%*
Lithium Supply (kt LCE):													
SQM		**48**	**48**	**48**	**50**	**55**	**63**	**90**	**139**	**149**	**161**	**177**	**177**
Atacama (Chile)	brine	48	48	48	50	55	63	85	116	116	126	132	132
Cauchari-Olaroz JV (Argentina)[1]	brine	0	0	0	0	0	0	5	13	13	15	25	25
Mt. Holland JV (Australia)[2]	spodumene	0	0	0	0	0	0	0	10	20	20	20	20
Albemarle		**56**	**56**	**63**	**73**	**82**	**99**	**137**	**165**	**165**	**165**	**175**	**185**
La Negra 1-3, Atacama (Chile)	brine	21	21	24	28	37	44	62	80	80	80	80	80
Greenbushes / Talison JV (Australia)[3]	spodumene	30	30	34	40	40	50	70	80	80	80	90	100
Clayton Valley (Nevada)	brine	5	5	5	5	5	5	5	5	5	5	5	5
FMC (Hombre Muerto / Argentina)	*brine*	**18**	**18**	**18**	**19**	**20**	**22**	**28**	**35**	**42**	**42**	**42**	**42**
Tianqi (Greenbushes / Talison JV, Australia)[3]	*spodumene*	**30**	**30**	**34**	**40**	**40**	**50**	**70**	**80**	**80**	**80**	**90**	**100**
Other Brine Producers		**0**	**2**	**7**	**12**	**14**	**23**	**33**	**55**	**55**	**58**	**68**	**68**
Lithium Americas - Cauchari-Olaroz JV (Argentina)[1]	brine	0	0	0	0	0	0	5	13	13	15	25	25
Orocobre (Olaroz, Argentina)	brine	0	2	7	12	14	23	28	43	43	43	43	43
China various	*brine/spodumene*	**10**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**
Other Spodumene Producers		**0**	**0**	**2**	**40**	**79**	**123**	**151**	**172**	**193**	**208**	**219**	**230**
Neometals/Ganfeng/MinRes (Mt. Marion, Australia)[4]	spodumene	0	0	0	25	50	50	50	50	50	50	50	50
Galaxy (Mt. Cattlin, Australia)	spodumene	0	0	2	15	20	20	20	20	20	20	20	20
AMG (Mibra, Brazil)	spodumene	0	0	0	0	2	5	10	10	10	14	14	14
Pilbara Minerals (Pilgangoora, Australia)	spodumene	0	0	0	0	5	30	44	55	66	77	88	99
Altura (Pilgangoora, Australia)	spodumene	0	0	0	0	2	18	27	27	27	27	27	27
Nemaska (Whabouchi, Quebec)	spodumene	0	0	0	0	0	0	0	0	0	0	0	0
Kidman Mt. Holland JV (Australia)[2]	spodumene	0	0	0	0	0	0	0	10	20	20	20	20
Supply loss due to unexpected outages (5%)					**(13)**	**(16)**	**(20)**	**(26)**	**(33)**	**(35)**	**(37)**	**(40)**	**(41)**
Total Supply		**162**	**174**	**192**	**240**	**295**	**379**	**502**	**632**	**668**	**696**	**751**	**780**
Supply Growth y/y			*7%*	*10%*	*25%*	*23%*	*29%*	*32%*	*26%*	*6%*	*4%*	*8%*	*4%*
Surplus / (Deficit)		**12**	**2**	**4**	**30**	**58**	**109**	**189**	**273**	**257**	**229**	**221**	**193**

[1] SQM and Lithium Americas have 50/50 JV for Cauchari-Olaroz (Argentina) expected to produce 25kt in 2019 and another 25kt by 2021. Shares shown separately.

[2] SQM and Kidman Resources have a 50/50 JV with plans to build the Mt. Holland project to product 40kt by 2021. Shares shown separately.

[3] ALB and Talison/Tianqi have a 50/50 JV at the Greenbushes mine in Australia. Shares shown separately.

[4] Ganfeng / Mineral Resources each own 43.1% interest in Mr.Marion, and Neometals owns 13.8%.

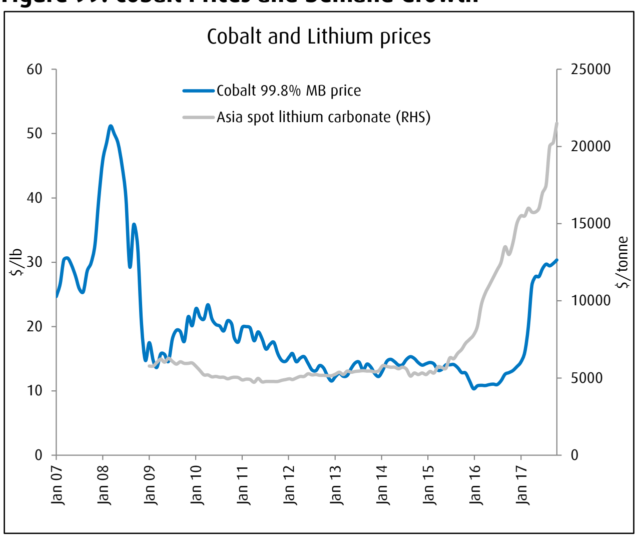
Source: Company Reports, Industry Reports, BMO Capital Markets

2. Cobalt: Solving for Complex Supply-Constraints

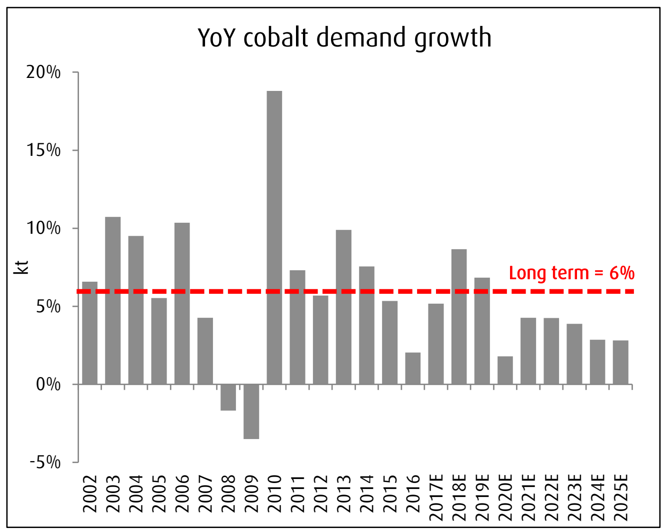
Bottom Line: Cobalt looks to be the main constraint on battery market growth. Even without a rise in electric vehicle demand we foresee a tight market, while overreliance on the Democratic Republic of Congo (DRC) on the supply side cannot be avoided. We expect aggressive substitution and scrap recovery over the coming years, but not before further price gains. A doubling of the cobalt spot price over the coming couple of years is not out of the question.

Over the past year, cobalt experienced a significant rally due to a variety of factors including continued growth in smartphone sales the decrease of 0.5% YoY in the 2017 global cobalt mining supply (weaknesses at Glencore operations and disputes at GTL's Big Hill primary cobalt tailings operation saw DRC output fall by ~4kt) and China's policy to phase out LFP battery in favour of cobalt containing NMC have left battery manufacturers scrambling to find a cobalt supply. Cobalt also has a complex value chain with next to no primary supply. Prices have now risen by over three-fold from the December 2015 low to levels last seen just before the GFC, at ~$38/lb. This makes cobalt the best performer of the commodities we cover over the past year in terms of price gains, and at current spot market pricing a market worth $8.4B per annum.

Figure 99: Cobalt Prices and Demand Growth



Source: Metal Bulletin, BMO Capital Markets



Source: CRU, CDI, BMO Capital Markets

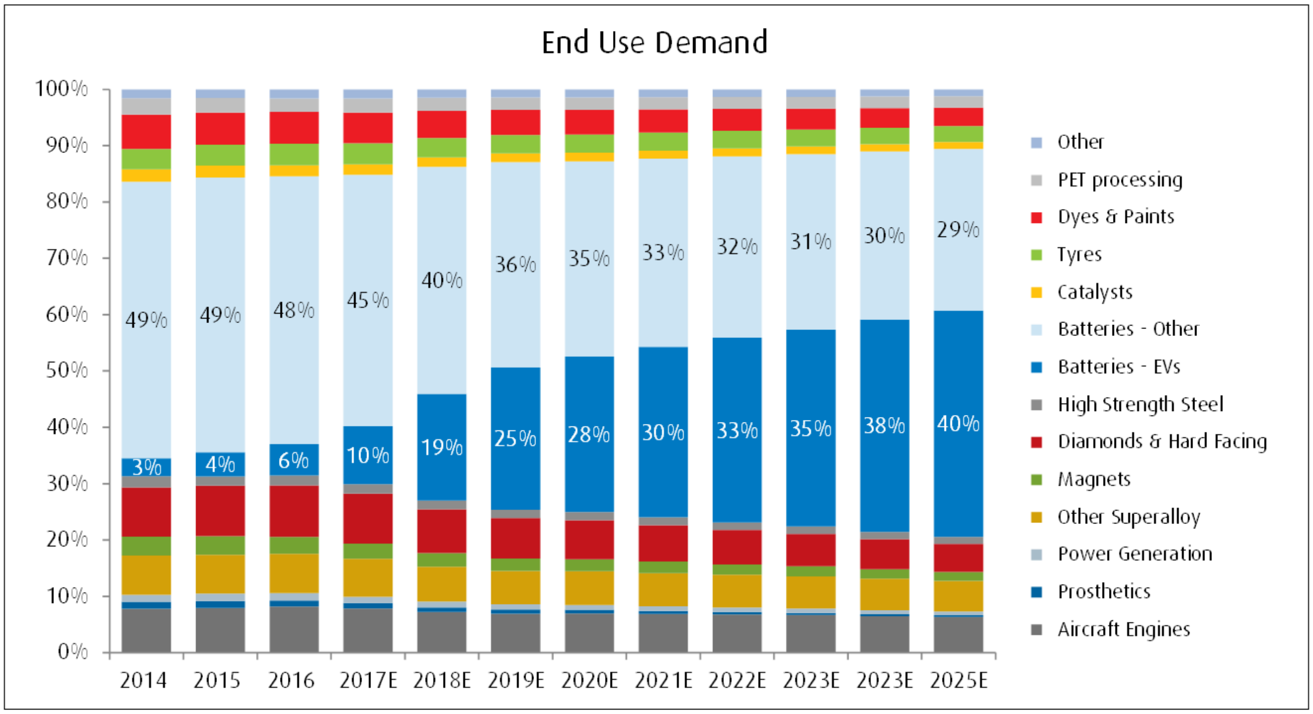
DEMAND: EVs Will Overtake Conventional Cobalt Usage From 2022 Onward

While we have seen other commodities growing their share of consumption through battery growth, cobalt has been down this path already. Around 55% of cobalt is already going into rechargeable batteries, compared to lithium's ~40% and nickel's ~5%, which has resulted in an industry-leading trend demand growth of 6.1% (CAGR) since 2010. Cobalt demand has grown from ~40kt in 2000 to exceed 100kt for the first time on our estimates this year.

Smartphone batteries are still the main end use market for cobalt, representing around a quarter of total demand, and we believe that the LCO battery will not be replaced anytime soon. From ~300 million units in 2010, global shipments are now ~1,500 million units, with average cobalt content ~16 grams each. This alone has added over 20kt to annual cobalt demand over the same period.

However, while we believe that portable electronics will remain central to cobalt demand, there will be a slight downtrend in this area.

Figure 100: Cobalt Demand Breakdown Overtime



Source: CDI, BMO Capital Markets

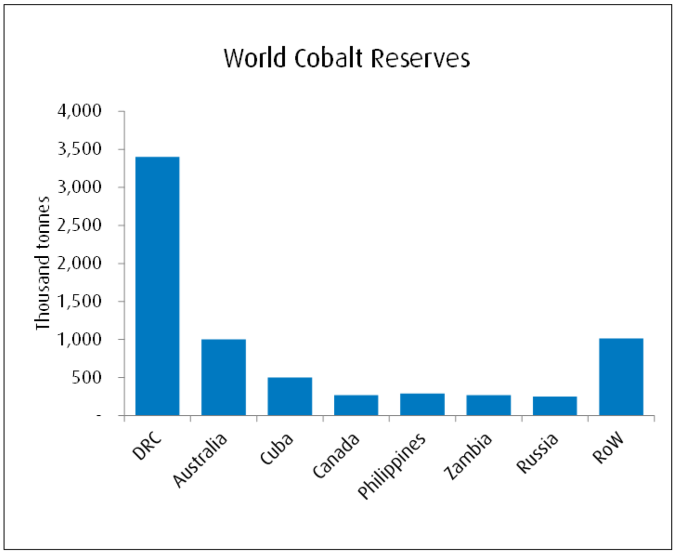
Unlike the portable electronics market, a variety of cathode materials are used in EV batteries. Some have cobalt in the mix, others do not and some are looking to switch to chemistries that contain cobalt. Traditionally, Chinese manufacturers have favoured cobalt-free lithium-iron-phosphate (LFP) batteries given their lower cost however the government is in the process of prioritizing the higher battery quality technologies. As a result, the general market expectation is that Chinese battery producers will shift to the NMC (nickel-manganese-cobalt) EV battery chemistry favoured in the rest of the world due to high energy density capabilities allowing for increased range. Tesla will also continue to drive its own path with nickel-cobalt-aluminum (NCA) technology, with cathodes of around 9% cobalt by weight. But increasing EV demand is only part of cobalt's story.

SUPPLY: A High Risk Supply Side Puts Cobalt in a Unique Position

Cobalt's supply side is unique among its peers because of its heavy reliance on the Democratic Republic of the Congo (DRC) and buffers against raw material constraints are limited. Currently, the DRC is responsible for 60% of mined cobalt units. Given this is one of the few supply regions across the world where existing mines can creep capacity, DRC dependence is only going to grow. We see the DRC representing 67% of mined cobalt units in 2025.

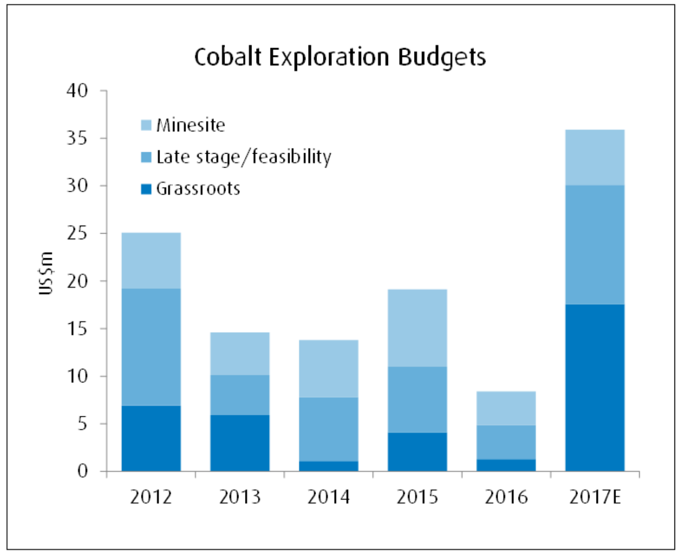
The level of DRC risk in cobalt supply cannot be underplayed. In our view, the wider market has become sanguine to the geopolitical risk in that country, and while the majority of cobalt is mined in Katanga Province, a long way from the capital Kinshasa, turbulence has caused issues in the past. This country, of course, was subject to the deadliest conflict in modern African history less than 20 years ago. Unrest is now surfacing again as protests against long-standing President Joseph Kabila have intensified, and elections will only be held in December 2018. **We do not assume any major issues in our modelling, but this concentrated nature means that the risk of potential supply shocks remain high.**

Figure 101: The DRC Contains Roughly Half of Global Reserves



Source: USGS, BMO Capital Markets

Figure 102: Cobalt Exploration Has Surged



Source: S&P Global, BMO Capital Markets

Some of the DRC's cobalt supply, unfortunately, also has come from the artisanal mining sector, which was recently exposed by Amnesty International for abhorrent human rights abuses and child labour. China's Zhejiang Huayou Cobalt, which supplies cobalt to some of the largest LIB and electronics companies in the world, was called out for sourcing some of its supply from these unethical operations. These revelations have caused a tremendous amount of pressure for all companies to review supply chains and Apple now treats cobalt as a "conflict mineral" requiring suppliers to agree to independent audits. In our view, this "cleaning up" will only intensify as consumers increasingly push companies to ensure that their cobalt supply comes from ethical mining operations or perhaps replace it altogether. However, as we will see in the next section, finding a substitute for cobalt is a very difficult endeavor and even the much-anticipated NMC811 chemistry contains 10% cobalt.

We expect that electronics companies will continue to be reliant on the DRC for the next four to five years. However, the cobalt supply chain is expected to loosen a bit as we view the 2017 DRC decrease in output as a blip as the Roan Tailings project for the Eurasian Resources Group is set to ramp up from 2018 onwards and a restart at Glencore's Katanga facility is expected to begin shortly. We therefore anticipate that the DRC will continue to be the major driver of 9% and 13% YoY growth in global mined cobalt output over 2018 and 2019, respectively.

Volkswagen's notable failure to secure long-term cobalt supply via tender shows the direct implications of this supply-side scenario. And, as a result, we expect car companies to lean on battery makers to spend more R&D dollars to accelerate reductions in cobalt content or replace it altogether. In our view, the trend we see in the development of an NMC cathode such as NMC811, which reduces the cobalt content by a third, would have happened anyway given cobalt's DRC exposure. No purchasing manager wants to be so reliant on supply of a critical raw material from a single supply source, particularly one with a poor human rights track record and the threat of political instability. However, as we saw earlier, this may be difficult to achieve.

Another one of cobalt's main challenges is that it very, very rarely will justify its own project. The vast majority of cobalt supply globally is either from a primary copper or primary nickel operation as a by- or co-product stream. The cobalt price, while potentially helping with overall mining costs through credits, will rarely justify development of a project on its own. For example, for most nickel-based projects, even a five-fold increase in cobalt price barely moves project IRR. Thus, unlike its battery peer lithium, there are next to no projects that could come to market in short order. Even with funding in place the process plant needed for cobalt is many times more complex than that for spodumene.

PRICE OUTLOOK: Cobalt's Role Is Expected to Diminish, But Not for Awhile

Unlike lithium, where the cathode chemistry has relatively little impact on overall demand, cobalt's altering cathode market share assumptions can have a large impact. The shift by China from LFP to NMC chemistry will have a tremendous impact on cobalt prices. However, there is also a large push to reduce cobalt content within the NMC family with NMC811 (which uses a quarter of the cobalt content) being viewed as the Holy Grail.

Therefore, we model an aggressive shift away from NMC111 towards NMC622 chemistry from 2020 onwards, which amounts to a halving of contained cobalt on a like-for-like basis. By 2025, we estimate that NMC622 will have 60% of the overall market share, becoming the standard EV cathode chemistry of choice. We also assume that, after a decline in market share over the coming years, some Chinese manufacturers will choose to sustain LFP cathode use in EVs in light of tight cobalt supply, keeping the overall market share at 20%. Meanwhile, Tesla's NCA maintains market share more or less in line with the overall market.

Figure 103: Our Base Case Calculation for EV Cobalt Demand

	2014	2015	2016	2017E	2018E	2019E	2020E	2021E	2022E	2023E	2024E	2025E
Key EV Assumptions:												
Global light vehicle sales (millions)	86	89	92	94	95	98	100	102	104	106	108	110
EV Market Penetration Rate (BEV/PHEV of total car sales)	0.5%	0.6%	0.8%	1.0%	1.8%	3.6%	5.1%	6.0%	6.8%	7.7%	8.7%	10.0%
EV Car Sales (millions)	0.4	0.5	0.8	0.9	1.8	3.5	5.1	6.1	7.1	8.2	9.3	11.0
NCA share	*9%*	*10%*	*11%*	*11%*	*11%*	*11%*	*11%*	*11%*	*10%*	*10%*	*10%*	*10%*
LFP share	*30%*	*35%*	*35%*	*31%*	*27%*	*25%*	*22%*	*20%*	*20%*	*20%*	*20%*	*20%*
LMO share	*5%*	*5%*	*5%*	*5%*	*4%*	*4%*	*3%*	*3%*	*2%*	*2%*	*1%*	*1%*
NMC 111 share	*56%*	*50%*	*49%*	*53%*	*50%*	*49%*	*39%*	*27%*	*23%*	*18%*	*13%*	*7%*
NMC 622 share	*0%*	*0%*	*0%*	*1%*	*8%*	*12%*	*25%*	*40%*	*45%*	*50%*	*55%*	*60%*
NMC 811 share	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*1%*	*2%*
EV Car Co Content (kg per kWh)	0.20	0.18	0.18	0.19	0.20	0.20	0.19	0.18	0.17	0.17	0.16	0.15
Average pack size across BEV + PHEV (kWh)	26.7	28.5	29.3	28.7	29.0	29.4	29.7	30.0	30.4	30.7	31.1	31.4
Cobalt Demand* (kt):												
EVs	**3**	**4**	**5**	**10**	**21**	**29**	**33**	**38**	**42**	**47**	**53**	**59**

*assumes purchase 1 year in advance of demand

Source: Industry Reports, Bloomberg, BMO Capital Markets

To allow for the time gap between battery manufacture and EV demand, we assume raw materials are purchased one year in advance of EV sales (i.e., 2018's EV sales translate to cobalt demand in 2017). Given rising EV sales and the reduction in LFP cathode use, cobalt demand rises from 5kt last year and 10kt in 2017 to 33kt by 2020 and 59kt by 2022, even assuming the shift to NMC622. As a result, EVs overtake portable electronics in terms of cobalt demand by 2022, and should account for 40% of total demand by 2025.

Even if EV penetration is lower than we envision, our scenario analysis shows that cobalt prices will still go up. Between 2016 and 2025, we see cobalt demand in batteries growing by 53kt, which breaks down into 54kt of EV demand growth, a 2kt net decline in portable electronics and 1kt of growth in energy storage.

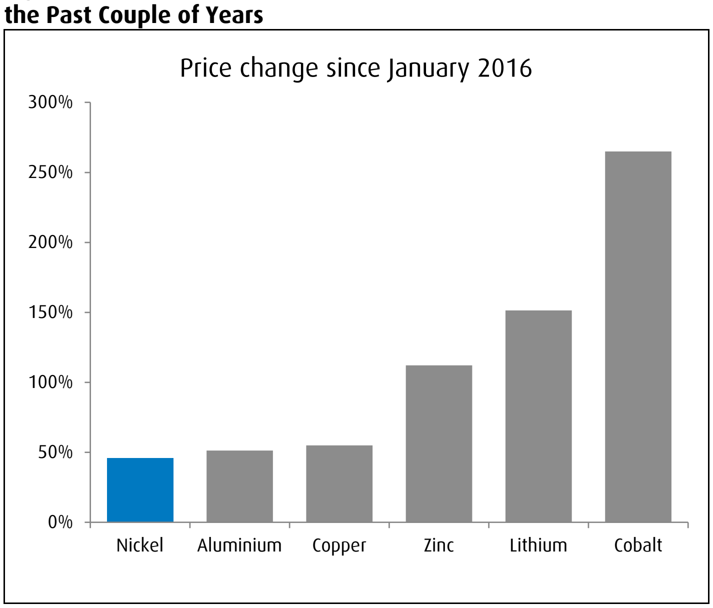
For further details on the demand and supply of cobalt, see the full Global Commodities Research report titled *Cobalt: Solving for a Supply-Constrained Market*, by Colin Hamilton dated December 4, 2017.

3. Nickel: Driven by Stainless Steel, Not Batteries (for now)

Bottom Line: We expect nickel to underperform base metal peers again in 2018. The resurgence of nickel pig iron (NPI) output, based on increased volumes of Indonesian ore, marks a comeback of the major deflationary element in the market. **However, the long-term story is a good one. Batteries will lead the way, and EV cathode chemistry must and will shift to higher nickel content over time.** We believe there will be market bifurcation in the 2020s as the demand for nickel from non-stainless applications first matches, then exceeds, Class I supply. Calling the timing on this is difficult, but strategic decisions from suppliers of refined material to sit on assets and thus accelerate this process would certainly make us more bullish.

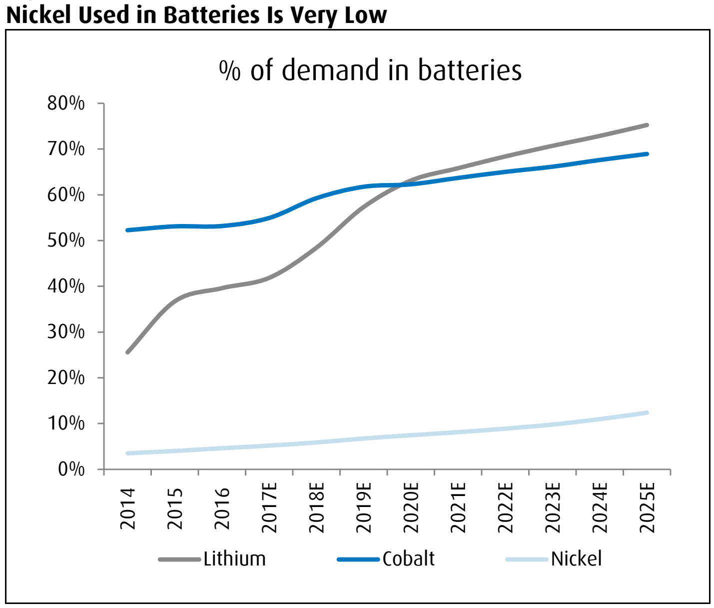
If 2016 was the year of lithium and 2017 that of cobalt, those hoping for a nickel catch-up are likely to be disappointed. Quite simply, only 5% of nickel currently goes into batteries, and less than 1% into EV batteries. This is well below the levels for lithium (42%, 25%) and cobalt (55%, 10%). Thus, for all the EV exuberance, nickel is still a stainless steel driven market at the present time, and will continue to be one in the near future.

Figure 104: Nickel Has Underperformed Peers Over the Past Couple of Years



Source: LME, Bloomberg, BMO Capital Markets

Figure 105: Compared to Lithium and Cobalt, the Proportion of Nickel Used in Batteries Is Very Low



Source: Wood Mackenzie, INSG, BMO Capital Markets

DEMAND: Still About Stainless, With Battery Impact Felt in the 2020s

Nickel prices have always cycled around with stainless steel trends. Partly owing to the nature of the surcharge mechanism, stainless producers rush to buy nickel when demand is good and prices rising, and vice versa. However, looking past the cycles, the longer-term trend for global stainless output growth is strong at +5%, helping nickel demand. Given it is hedged between the consumer and industrial economies and is still gaining market penetration in many areas, we expect stainless growth to continue to exceed global GDP. Moreover, over the coming years, the shift within stainless towards the higher quality, higher nickel content 300-series material continues. For comparison, nickel demand in non-stainless applications has grown at a trend rate of 1.9%pa – stainless has become increasingly important over time.

Looking longer term, battery demand will become significantly more important for nickel, and overtake stainless as the main demand driver. Unlike cobalt, nickel rechargeable batteries are not used extensively in integrated battery portable electronics. Nickel-cadmium and nickel metal hydride (NiMH) batteries are though used in high drain, long lifespan applications such as digital cameras, medical devices, and GPS units. However, electric vehicles are certainly likely to be the growth area in nickel batteries over the coming years.

Moreover, EV cathode chemistry is becoming increasingly nickel rich. Nickel helps to increase energy density in the battery (but at the expense of stability) and given the much-discussed potential cobalt constraint, we expect car companies to lean on battery makers to accelerate nickel substitution of cobalt. We model an aggressive shift away from NMC111 (~20%Ni in cathode) towards NMC622 (~36%Ni) chemistry from 2020 onwards, which amounts to a doubling of contained nickel on a like-for-like basis.

Figure 106 shows our calculation for nickel demand. To allow for the time gap between battery manufacture and EV demand, we have assumed raw materials are purchased one year in advance of EV sales (i.e., 2018's EV sales translate to nickel demand in 2017). Between 2016 and 2025, we see nickel demand in EV batteries growing by 215kt, equivalent to 10% of the current market size.

Figure 106: Our Base Case Calculation for EV Nickel Demand

	2014	2015	2016	2017E	2018E	2019E	2020E	2021E	2022E	2023E	2024E	2025E
Key EV Assumptions:												
Global light vehicle sales (millions)	86	89	92	94	95	98	100	102	104	106	108	110
EV Market Penetration Rate (BEV/PHEV of total car sales)	0.5%	0.6%	0.8%	1.0%	1.8%	3.6%	5.1%	6.0%	6.8%	7.7%	8.7%	10.0%
EV Car Sales (millions)	0.4	0.5	0.8	0.9	1.8	3.5	5.1	6.1	7.1	8.2	9.3	11.0
NCA share	*9%*	*10%*	*11%*	*11%*	*11%*	*11%*	*11%*	*11%*	*10%*	*10%*	*10%*	*10%*
LFP share	*30%*	*35%*	*35%*	*31%*	*27%*	*25%*	*22%*	*20%*	*20%*	*20%*	*20%*	*20%*
LMO share	*5%*	*5%*	*5%*	*5%*	*4%*	*4%*	*3%*	*3%*	*2%*	*2%*	*1%*	*1%*
NMC 111 share	*56%*	*50%*	*49%*	*53%*	*50%*	*49%*	*39%*	*27%*	*23%*	*18%*	*13%*	*7%*
NMC 622 share	*0%*	*0%*	*0%*	*1%*	*8%*	*12%*	*25%*	*40%*	*45%*	*50%*	*55%*	*60%*
NMC 811 share	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*1%*	*2%*
EV Car Ni Content (kg/per kWh)	0.25	0.24	0.24	0.27	0.30	0.32	0.37	0.42	0.44	0.45	0.47	0.49
Average pack size across BEV + PHEV (kWh)	26.7	28.5	29.3	28.7	29.0	29.4	29.7	30.0	30.4	30.7	31.1	31.4
Nickel Demand (kt)*:												
EVs	**4**	**5**	**7**	**15**	**33**	**56**	**77**	**94**	**113**	**137**	**170**	**212**

*assumes purchase 1 year in advance of demand

Source: Industry Reports, Bloomberg, BMO Capital Markets

SUPPLY: Rising NPI and Falling Costs a Challenging Combination

While nickel demand has exceeded growth rates seen for most industrial metal peers, this has been more than matched by available supply over recent years. Essentially, the nickel industry is still coming to terms with the disruption seen from the initial emergence, and subsequent optimisation of nickel pig iron production, which has grown from nothing in 2005 to now account for over a quarter of global nickel units. On the back of this, supply of nickel grew over 50% between 2009 and 2013. Owing to this, the split between sulphide and laterite ore has moved from one of balance to one where laterites now account for ~65% of global supply, a figure which is set to rise to over 70% in the coming years. Taking the ore for NPI aside, nickel output at existing assets has been rather consistent, with the occasional disruption just as seen with base metal peers.

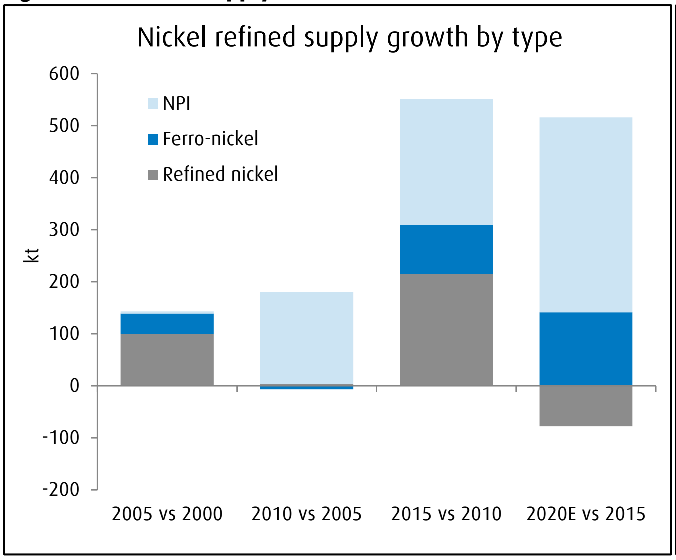
This highlights just how important NPI has been in altering the dynamics of the nickel industry. However, from 2013-2016 NPI output fell, as lower prices brought about the closure of much of the high-cost non-rotary kiln Chinese capacity and shipments of ore from Indonesia fell to zero after the 2014 ore ban enforcement. Over this period, the main deflationary pressure on nickel was actually removed, and the potential for a raw material constraint (feeding through into refined shortage) was increasing.

This is why the reversal of the Indonesian ore ban in January last year was so important. Indonesian ore is very much the preferred feedstock for NPI output, being higher quality (~1.7% versus ~1.0% average for Filipino material) and thus both increasing productivity and lowering cost. Using this ore can make ~10%Ni NPI – perfect for austenitic stainless steel – versus the 6-8% NPI from Philippines origin ore, which requires blending with higher quality material to make austenitic steel.

The importance of NPI costs to the global nickel industry simply cannot be overstated. Chinese stainless steel producers are the marginal nickel buyers, and often the marginal producers given their vertical integration into NPI. Because of this, the marginal cost of making NPI essentially sets the nickel price, and has done since 2014. The LME price can and does move above or below this level at various points in the cycle; however, the cost of NPI acts as an anchor. And of these costs, 50-60% is the delivered ore price. Thus, the return of low-cost Indonesian material and its need to displace existing tonnage will likely see some downward push on costs from the current $13,000/t ($6/lb) level. For example, a drop of 15% in ore price to the levels seen in 2013 (the last time Indonesia shipped significant ore volumes) would knock ~$750/t off current NPI costs – more if freight rates also drop. Nickel ore oversupply is a major issue for the nickel market.

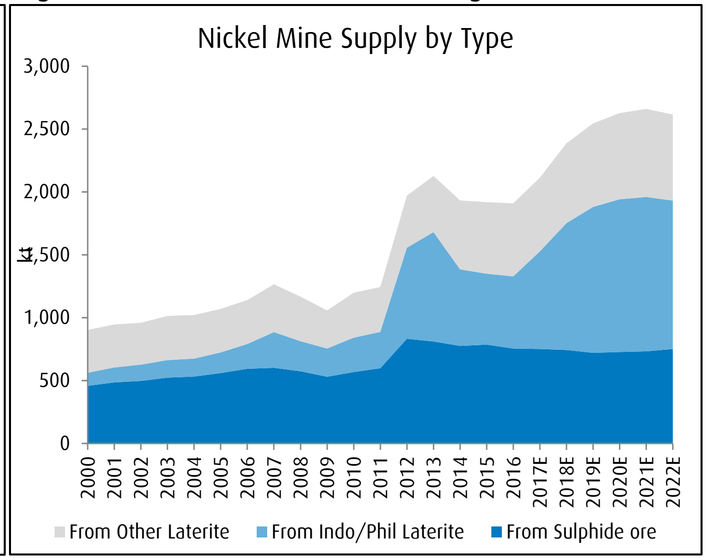
To serve the EV battery boom, nickel sulphate (Ni_2SO_4) is required. There has been some commentary in the market that such material cannot be produced from lateritic ores. This is simply untrue – any high-purity nickel metal unit, many of which are currently produced from laterite – can be dissolved in sulphuric acid to form nickel sulphate upon evaporation. What is true is that the process to sulphate from sulphide ore is more direct and generally lower cost, while the need to utilise difficult-to-process laterite ores will drive some nickel sulphate premium over LME nickel through the cycle.

Figure 107: Nickel Supply Has Grown This Decade...



Source: INSG, Wood Mackenzie, BMO Capital Markets

Figure 108: ...With Laterite Ore Dominating Growth



Source: INSG, Wood Mackenzie, BMO Capital Markets

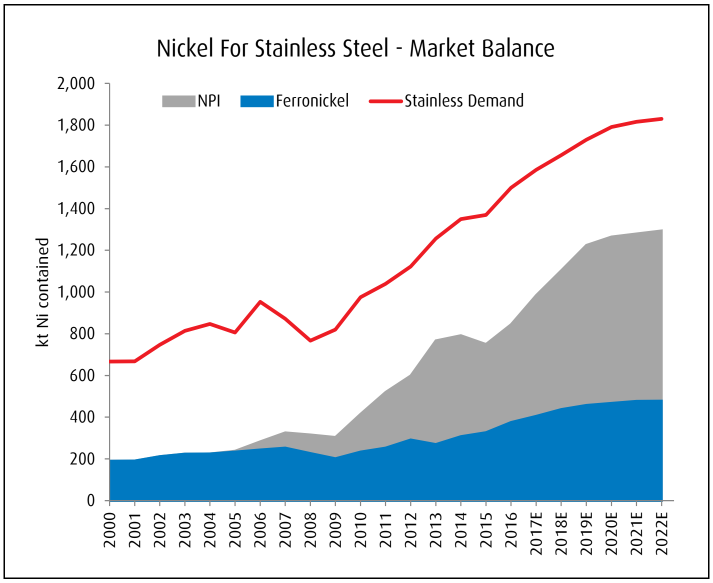
PRICE OUTLOOK: Shifting Towards a Two-Tier Market Over Time

Going forward, and given the growth in nickel for batteries, analysis should really be considering the nickel market in two parts. First is the stainless balance, which we consider as demand from stainless steel minus combined ferronickel and nickel pig iron supply. Stainless mills much prefer purchasing ferronickel and NPI, where they pay for nickel and get iron for free, to paying full LME/SHFE rates for refined nickel plus paying a premium on top. The high purity Class I nickel is more expensive to buy, and more expensive to melt. This balance shows stainless demand at ~1,645kt currently, versus combined FeNi/NPI supply at 1,100kt. Essentially, stainless steelmakers are 545kt short of the types of nickel they would prefer – they are more than happy to absorb all the growth in iron-nickel material in 2018-19.

Flipping this balance on its head gives the Class I nickel balance. This is calculated via non-stainless steel demand (including batteries), currently 580kt, versus high purity refined nickel supply, currently 1,100kt. The non-stainless applications, being plating and super alloys as well as batteries, need the high quality supply. At present, there is 520kt more supply of this than such applications demand.

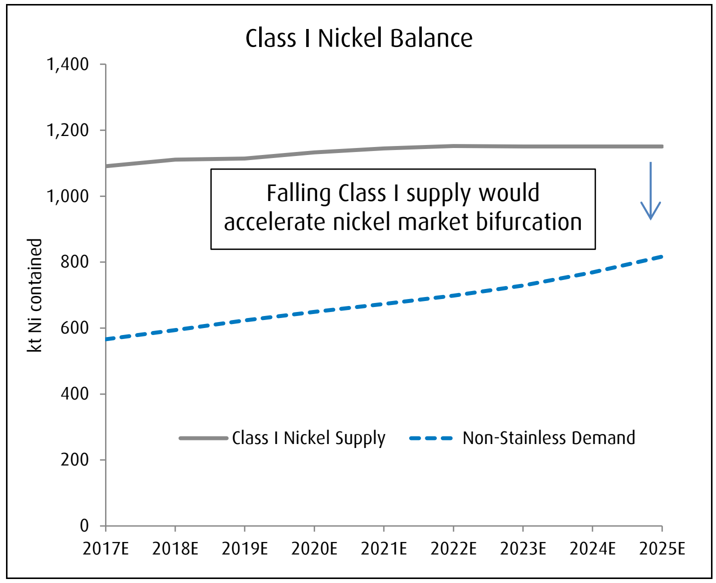
As the Class I surplus dwindles, this is when we expect to see the much-discussed market bifurcation between ferronickel/NPI and nickel metal emerge. At this point (bearing in mind commodity prices are not forward looking) the LME nickel price will move to a level to incentivise all available nickel units to market. This is the long-awaited boon that nickel metal producers have been waiting for, and should result in strong cash flow for the survivors. On our modelling, this process should start from 2025 onwards.

Figure 109: At Present, Stainless Steel Producers Are Short of the Forms of Nickel They Prefer to Use...



Source: ISSF, ICSG, BMO Capital Markets

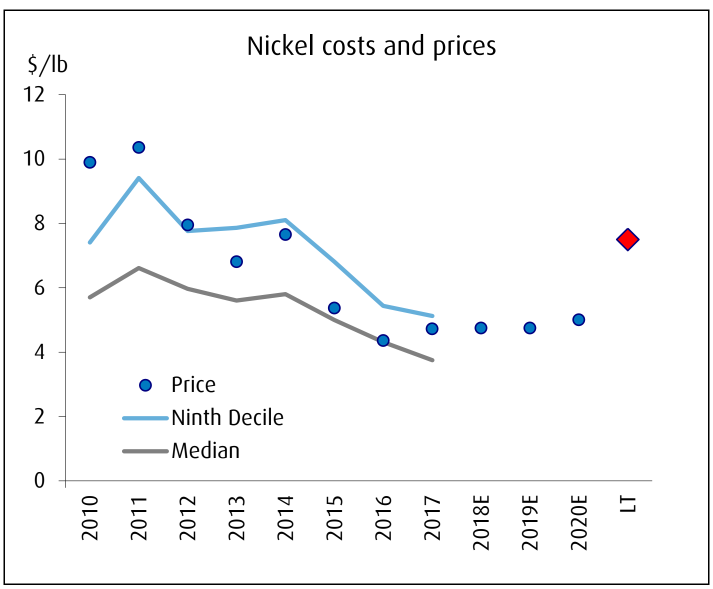
Figure 110: ...While Supply of Nickel Metal Strongly Exceeds Non-Stainless Nickel Demand



Source: Wood Mackenzie, ICSG, BMO Capital Markets

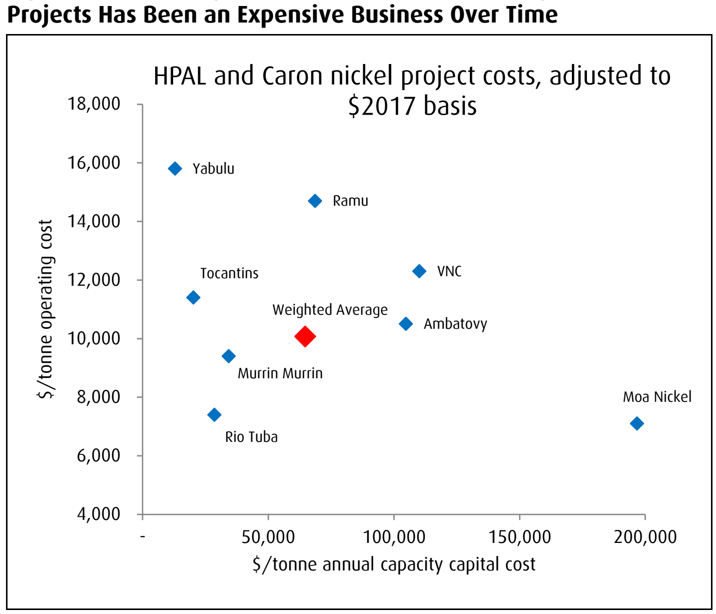
So where would nickel prices go to after bifurcation? FeNi and NPI prices would still be set by the marginal costs of Chinese supply, but LME grade nickel prices would have to move to a level to incentivise new projects, most likely based on HPAL or Caron technology given the lack of new sulphide options. Such projects have had a wide range of capital and operating costs (and thus incentive prices) over time, but we expect a $16,530/t ($7.5/lb) level is a good equilibrium price to consider, with potential overshoots as the Class I deficit emerges.

Figure 111: Nickel Has Been Trading Into the Cost Curve for the Past Five Years



Source: LME, Wood Mackenzie, BMO Capital Markets

Figure 112: Building New HPAL or Caron Technology Nickel Projects Has Been an Expensive Business Over Time



Source: Wood Mackenzie, BMO Capital Markets

For further details on the demand and supply of nickel, please see the full Global Commodities Research report, *Nickel: NPI Overpowers Batteries* for 2018, published on January 4, 2018 by Colin Hamilton.

Battleground #4 → Race to Secure Key Raw Materials

Lithium, Cobalt, and Nickel Suppliers

Bottom Line: Extraction methods are pretty standard, but the relationships between these companies and battery manufacturers are not. Gone are the days where there is a homogenous product produced for all purposes. Indeed, many companies have shared the new challenges they face when dealing with clients: mainly that they have different needs and servicing them requires an intimate understanding of those needs. It may be a different grade, or a different composition. Nonetheless, gone are the days where one product fits all.

Figure 113: Only So Many Liquid Options for Public Lithium Exposure

Company	Ticker	Exch.	Rating	Target	Mkt Cap ($M)	EBITDA[1]		Lithium Production (kt LCE)		Net Debt (M)	EV (M)	Main Production Region (s)	Development Projects	Share Price Performance 3-month	Share Price Performance	
						2017E	2018E	2017E	2022E[2]						6-mo	12-mo
Large Lithium Producers																
Albemarle	ALB	NYSE	OP	$160.00	$11,845	$876	$989	73	165	$1,000	$12,338	Australia, Chile, US	Argentina, Australia, Chile, US	-25%	-5%	14%
SQM	SQM	NYSE	Mkt	$60.00	$14,678	$863	$895	50	149	$357	$15,035	Chile	Argentina, Australia, Chile	-11%	26%	60%
Tianqi	002466	SHE			¥56,890	¥3,600	¥4,026	40	80	¥2,191	¥59,082	Australia	Australia	-25%	-14%	64%
Smaller Lithium Producers																
FMC	FMC	NYSE	Mkt	$90.00	$12,254	$621	$1,179	19	42	$1,672	$13,926	Argentina	Argentina	-8%	2%	43%
Galaxy Resources	GXY	ASX			A$1,235	A$56	A$141	15	20	A$31	A$1,266	Australia	Argentina, Australia, Canada	-22%	58%	3%
Jiangxi Ganfeng	002460	SHE			¥29,570	¥1,589	¥2,901	11	22	¥449	¥30,020	Australia	Australia	-33%	-11%	120%
Mineral Resources	MIN	ASX			A$3,282	A$464	A$582	11	22	-A$104	A$3,178	Australia	Australia	-6%	30%	39%
Neometals	NMT	ASX			A$196	A$4	A$4	3	7	-A$42	A$154	Australia	Australia	-23%	22%	-9%
Orocobre	ORE	ASX			A$1,399	-A$1	A$20	12	43	-A$79	A$1,320	Argentina	Argentina	16%	107%	64%
New Lithium Entrants In Construction																
Altura Mining	AJM	ASX			A$580	-A$4	-A$2		27	A$2	A$583		Australia	-28%	78%	81%
AMG	AMG	AMS			€1,229	€ 98	€ 111		10	C$3	C$1,232		Brazil	-1%	42%	134%
Lithium Americas	LAC	TSX			C$695	-C$14	-C$11		13	-C$10	C$684		Argentina	-20%	38%	54%
Pilbara Minerals	PLS	ASX			A$1,414	-A$25	A$1		44	-A$97	A$1,317		Australia	-3%	115%	59%
Notable Prospective Lithium Developers																
Advantage Lithium	AAL	TSXV			C$148								Argentina, US		155%	28%
Kidman Resources	KDR	ASX			A$636				20	A$6	A$641		Australia	32%	227%	267%
Lithium Power	LPI	ASX			A$115					-A$4	A$111		Chile	-26%	44%	35%
Lithium X	LIX	TSXV			C$222					-C$20	C$201		Argentina	26%	18%	10%
LSC	LSC	TSXV			C$183					-C$12	C$171		Argentina	-13%	-3%	205%
Nemaska	NMX	TSX			C$450					-C$67	C$384		Canada	-15%	22%	-2%
Neo Lithium	NLC	TSXV			C$205					-C$13	C$192		Argentina	2%	79%	46%

[1]FMC, ALB and SQM ND and EBITDA estimates from BMO, other companies provided by Fact Set consensus.

[2]2017E and 2022E lithium production estimates from BMO's supply/demand model.

Source: Company Reports, FactSet, BMO Capital Markets

Figure 114: Nickel Producers Ranked by Mined Output

Miners	Main Listing	Market Cap (US$ Mn)*	Mined Output (kt)	% Global	Refined Output (kt)	% Global
Vale	Brazil	69,466	248	11.4	236	11.5
Nornickel	Russia	32,793	201	9.2	212	10.3
Glencore	UK	80,854	106	4.9	138	6.7
Jinchuan Group Int. Resources Co. Ltd.	China (HK)	902	83	3.8	134	6.5
Anglo American Plc	UK	31,036	74	3.4	62	3.0
BHP Billiton	UK	125,712	59	2.7	71	3.5
PT Aneka Tambang	Indonesia	1,630	57	2.6	23	1.1
South32	UK	15,816	46	2.1	41	2.0
Nickel Asia	Philippines	1,014	38	1.7	30	1.5
Sherritt International	Canada	409	36	1.7	31	1.5
Eramet	France	3,728	35	1.6	55	2.6
Solway Investment Group	Switzerland	-	34	1.6	31	1.5
Terrafame	Finland	-	30	1.4	20	1.0
Cunico Resources	Netherlands	-	28	1.3	15	0.8
Lundin Mining Corporation	Canada	5,276	23	1.0	14	0.8
Western Areas NL	Australia	733	22	1.0	11	0.6
Larco	Greece	-	22	1.0	4	0.2
Jilin Ji En Nickel Industry Co. Ltd.	China	-	21	1.0	-	-
Pacific Metals	Japan	652	21	1.0	-	-
General Nickel Corp	US	-	19	0.9	-	-

*As of February 2018

Source: Bloomberg

Figure 115: Cobalt Producers and Development Companies

Producers	Main Listing	Nov 17 Market Cap (US$ Mn)	Feb 18 Market Cap (US$ Mn)	% Change
African Rainbow Minerals Ltd	S Africa	1,792	2,349	31%
Anglo American Platinum Ltd	S Africa	7,320	8,171	12%
China Molybdenum Co. Ltd	China (HK)	18,427	25,282	37%
Cobalt 27 Capital Corp.	Canada	146	342	135%
First Quantum Minerals Ltd	Canada	8,068	10,330	28%
Freeport McMoran	US	19,992	28,156	41%
GEM Co Ltd	China	4,210	3,854	-8%
Glencore Plc	UK	67,042	80,845	21%
Jinchuan Group Int. Resources Co. Ltd	China (HK)	678	902	33%
Katanga Mining	Canada	1,953	2,459	26%
Lundin Mining	Canada	5,250	5,276	0%
Metallurgical Corp. of China (MCC)	China (HK)	14,468	16,980	17%
Nornickel	Russia	41,197	32,793	-20%
Sherritt International Corp.	Canada	315	409	30%
Sumitomo Metal Mining Co. Ltd	Japan	11,430	22,118	94%
Umicore	Belgium	10,323	11,852	15%
Vale SA	Brazil	52,833	69,466	31%
Vedanta Resources	UK	2,741	3,238	18%
Zheijiang Huayou Cobalt	China	6,814	9,471	39%
Development Companies	**Main Listing**	**Nov 17 Market Cap (US$ Mn)**	**Feb 18 Market Cap (US$ Mn)**	**% Change**
Ardea Resources Ltd	Australia	99	103	4%
Berkut Minerals Ltd	Australia	14	7	-49%
Broken Hill Prospecting (Cobalt Blue)	Australia	5	8	55%
Castle Silver Resources Inc.	Canada	9	22	147%
Cblt Inc.	Canada	3	3	-5%
Clean TeQ	Australia	656	653	0%
Cobalt Blue Holdings Ltd	Australia	17	56	230%
Corazon Mining Ltd	Australia	16	17	9%
Cruz Cobalt Corp.	Canada	10	22	116%
Ecobalt	Canada	86	155	80%
First Cobalt	Canada	65	175	169%
Fortune Minerals Ltd	Canada	44	76	73%
Global Energy Metals	Canada	3	6	69%
Kings Bay Resources Corp.	Canada	4	3	-16%
LiCo Energy Metals	Canada	10	16	58%

Note: We are restricted on Ecobalt Solutions.
Source: Bloomberg

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Equity Research Analysts

Director of Canadian Equity Research
Bert Powell, CFA 416-359-5301

Associate Director – Canada
Hari Sambasivam 416-359-8357

Director of US Equity Research
Carl Kirst, CFA 212-885-4113

Associate Director – US
Todd J. Jonasz 212-885-4051

ENERGY

Oil & Gas – Integrateds
Randy Ollenberger 403-515-1502
Brendan Warn +44 (0)20 7664 8087

Oil & Gas – E&P
Jared Dziuba, CFA 403-515-3672
Phillip Jungwirth, CFA 303-436-1127
Ray Kwan, P.Eng. 403-515-1501
Joe Levesque 403-515-1557
Dan McSpirit 303-436-1117
David Round +44 (0)20 7664 8052
Brendan Warn +44 (0)20 7664 8087

Oil & Gas – Oilfield Services
Daniel Boyd, CFA 713-547-0812
Mike Mazar, CPA, CA, CFA 403-515-1538

MATERIALS

Base Metals & Mining
David Gagliano, CFA 212-885-4013
Alexander Pearce +44 (0)20 7246 5435
Edward Sterck +44 (0)20 7246 5421
Alex Terentiew 416-359-6319

Precious Metals & Minerals
Andrew Breichmanas, P.Eng. +44 (0)20 7246 5430
Andrew Kaip, P. Geo. 416-359-7224
Andrew Mikitchook, P.Eng., CFA 416-359-5782
Brian Quast, P. Eng., JD 416-359-6824
Ryan Thompson, CFA 416-359-6814

Commodity Strategy
Colin Hamilton +44 (0)20 7664 8172

Packaging & Forest Products
Mark Wilde, Ph.D. 212-883-5102
Ketan Mamtora 212-883-5121

Fertilizers & Chemicals
Joel Jackson, P.Eng., CFA 416-359-4250

INDUSTRIALS

Transportation & Aerospace
Fadi Chamoun, CFA 416-359-6775

Diversified Industrials
Devin Dodge, CFA 416-359-6774

Diversified Industrials & Industrial Distribution
R. Scott Graham 212-885-4077

Machinery
Joel Tiss 212-883-5112

Business & Industrial Services
Jeffrey M. Silber 212-885-4063

Mobility Equipment & Technology
Richard Carlson, CFA 212-883-5141

CONSUMER DISCRETIONARY

Retail - Broadlines/Hardlines
Wayne Hood 404-926-1590

Retail - Apparel & Specialty
John D. Morris 212-885-4016

Retailing/Consumer
Peter Sklar, CPA, CA 416-359-5188

Restaurants
Andrew Strelzik 212-885-4015

Toys & Leisure
Gerrick L. Johnson 212-883-5192

Auto Parts
Peter Sklar, CPA, CA 416-359-5188

Education
Jeffrey M. Silber 212-885-4063

Special Situations
Stephen MacLeod, CFA 416-359-8069
Jonathan Lamers, CFA 416-359-5253

CONSUMER STAPLES

Food Retail
Kelly Bania 212-885-4162

Food & Ag Products
Kenneth B. Zaslow, CFA 212-885-4017

Food & Beverage
Amit Sharma, CFA 212-885-4132

Retail - Personal Care and Household Products
Shannon Coyne, CFA 404-926-1591

HEALTHCARE

Biotechnology
M. Ian Somaiya 212-885-4038
Do Kim 212-885-4091
Matthew Luchini 212-885-4119

Managed Care/Facilities
Matthew Borsch, CFA 212-885-4094

Medical Technology
Joanne K. Wuensch 212-883-5115

Pharmaceuticals
Alex Arfaei 212-885-4033
Gary Nachman 212-883-5113

FINANCIALS

Canadian Banks
Sohrab Movahedi 416-359-7157

US Large Cap Banks & Specialty Finance
James Fotheringham 212-885-4180

US Banks
Lana Chan 212-885-4109

Insurance/Diversified Financials (Canada)
Tom MacKinnon, FSA, FCIA 416-359-4629

Diversified Financials (Canada)
Nik Priebe, CFA 416-359-4293

Financial Technology
Paulo E. Ribeiro 212-885-4079

REAL ESTATE

Real Estate Investment Trusts (Canada)
Heather C. Kirk, CFA 416-359-4030
Troy MacLean, CFA 416-359-8366

Real Estate Investment Trusts (US)
John P. Kim 212-885-4115
R. Jeremy Metz 212-885-4053

INFORMATION TECHNOLOGY

IT Services & Software
Keith Bachman, CFA 212-885-4010

Communications Equipment
Tim Long 212-885-4101

Information Technology
Thanos Moschopoulos, CFA 416-359-5428

Semiconductors
Ambrish Srivastava, Ph.D. 415-591-2116

Telecom/Media/Cable
Tim Casey, CFA 416-359-4860

Media and Internet
Daniel Salmon 212-885-4029

UTILITIES

Electric Utilities & Independent Power
Ben Pham, CFA 416-359-4061

US Pipelines & MLPs
Danilo Juvane, CFA 713-518-1267

MACRO

Investment Strategy
Brian G. Belski 212-885-4151
416-359-5761

Economics
Douglas Porter, CFA 416-359-4887
Michael Gregory, CFA 312-845-5025
416-359-4747
Earl Sweet 416-359-4407

Quantitative/Technical
Mark Steele 416-359-4641
Ken Hartviksen, CFA 416-359-6211

Exchange Traded Funds
Jin Li 416-359-7689

SPECIAL PROJECTS

Special Projects
Kimberly Berman 416-359-5611

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