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Q-Series

Tearing down the heart of an electric car: Can batteries provide an edge, and who wins?

Equities

Global

Automobiles

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Battery is key to success of EVs – UBS Evidence Lab tore down all cell types

The battery is the most expensive and most critical part of an electric car (25-40% of the vehicle's total value today). Winning in batteries means (1) turning electric cars into a true mass-market technology and (2) having a significant competitive edge – this holds true for both battery makers and auto OEMs. To find out who is best positioned to win, UBS Evidence Lab performed a unique teardown of the leading battery cells for electric vehicles (EV) from Panasonic/Tesla, LG Chem, Samsung SDI and CATL. The findings have a widespread impact on our view about auto OEMs, battery makers, the chemical and mining sector as well as the outlook for global battery commodities.

What were the biggest surprises?

We found out that Panasonic cells produced in the Tesla Gigafactory win the cost competition, with a cell cost of $111/kWh – a ~20% lead over second-placed LG Chem. Compared with our findings from the Model 3 teardown, Tesla's battery turns out to be $37/kWh or ~$2.8k/$2k cheaper per vehicle (long/short-range versions). Panasonic's cost lead is likely to shrink to ~10% as peers catch up through economies of scale and shift to NMC811 after 2020, though Panasonic won't stand still either.

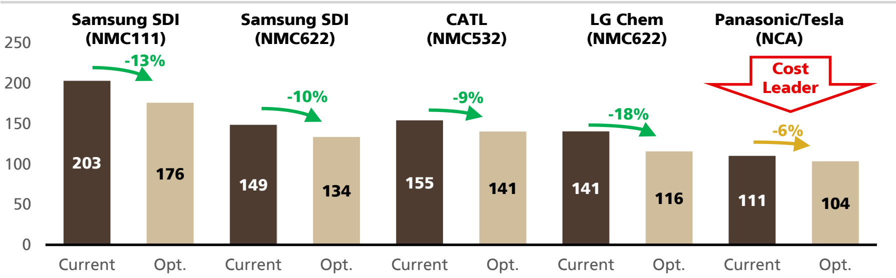
Widespread impact on batteries, autos, chemicals and commodities sector

In autos, the combination of Tesla's cost lead in the battery pack and technology lead in the battery management system gives the company a clear competitive advantage vs incumbents, at least temporarily. In batteries, while Panasonic leads in cost, we expect LG Chem to grow faster as most incumbent OEMs prefer not to use the cylindrical NCA cells, which are more difficult to control. We forecast a 973 GWh battery market in 2025 (equivalent to 19 Tesla Gigafactories), resulting in an average revenue CAGR of ~20% for the cell makers. We consider an oligopolistic structure with the five existing key players as the most likely outcome in 2025, as a breakthrough in cell chemistries is unlikely over that timeframe. Our interactive model flexes commodity prices and production set-ups to illustrate the impact on cell costs for each supplier.

Key stock ideas: Most and least favoured stocks on the theme

LG Chem is our top pick, whereas newly initiated CATL is a Sell. Tesla (raising EPS and PT) benefits most from the teardown findings, even though we remain Sellers as product mix is likely to soften. Amongst incumbents, Buy-rated VW and SAIC are best positioned to win. In commodities, we are positive on nickel and cautious on cobalt.

Figure 1: Battery cell cost today vs fully scaled up ($/kWh) – Panasonic leads



Source: UBS Evidence Lab Note: Optimized production scenario incl. full scale benefits

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Executive summary

Key conclusions

UBS Evidence Lab and P3, an engineering consultancy with strong expertise in the field of batteries for EVs, performed an in-depth physical and chemical analysis of the leading EV battery cell types. What are the most relevant and surprising conclusions?

- Panasonic wins the cell teardown. Its 2170 cells produced in the Tesla Gigafactory have a 20% cost advantage. The gap will likely narrow as Korean/Chinese peers approach the same scale, but we do not expect them to fully catch up. Only once the NMC811 chemistry becomes mainstream (not until the early 2020s) is there a chance to almost close the gap.
- We expect LG and CATL to be the fastest-growing battery suppliers, in spite of Panasonic's cost lead.
- An oligopolistic battery market structure, with five global battery players, looks the most likely scenario to us. As technological disruption is unlikely on a 2025 horizon, we see no business case for new entrants.
- Tesla benefits most. Its cost advantage can be defended at least temporarily because other OEMs will not switch to the cheaper NCA chemistry, in part because of Tesla's edge in the battery management system for NCA cells. Our model also shows Tesla has the most efficient electric powertrain of any carmaker.
- Contrary to our previous view, we now believe incumbent OEMs will be less profitable than Tesla in the EV space.

Battery cells back to basics

NMC
Nickel-manganese-cobalt

NCA
Nickel-cobalt-aluminium

NMC 111/622/811
Numbers describe the relative portions of the three active materials

Cylindrical/pouch/prismatic
Describe the format of the battery cells

Figure 2: Five key numbers to remember

$30/kWh Gigafactory's cost lead over LG Chem

$84bn battery market size in 2025, vs $23bn today

$2.7-3.8k Tesla's cost advantage over competitors at pack level

Tesla saves another **~$2,000** battery cost per car through superior electronics

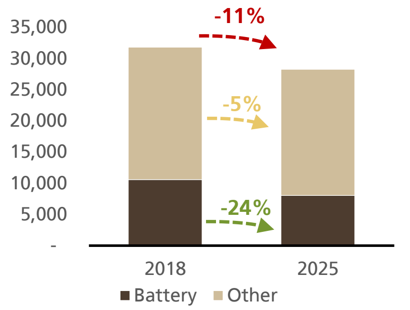
80% combined market share of top-5 battery players 2025E

Source: UBS estimates

The battery cell is key to the success of electric cars, and that's why UBS Evidence Lab tore down all cell types

The battery represents 25-40% of the total cost of an electric car today, which makes it by far the most expensive part. Reducing battery cost and improving battery performance is the most crucial driver to (1) make electric cars a true mass-market technology and (2) win in a highly competitive battery and auto OEM landscape. The implications are far-reaching and affect the commodities markets and mining companies, the chemical sector, and several others. To gain unique insights into the different cell types in terms of **technology, chemical composition, manufacturing process and costs**, UBS Evidence Lab tore town the industry-leading cell types from Panasonic (Tesla Gigafactory), LG Chem, Samsung and CATL.

Figure 3: Why the battery moves the needle… ($ content per car)

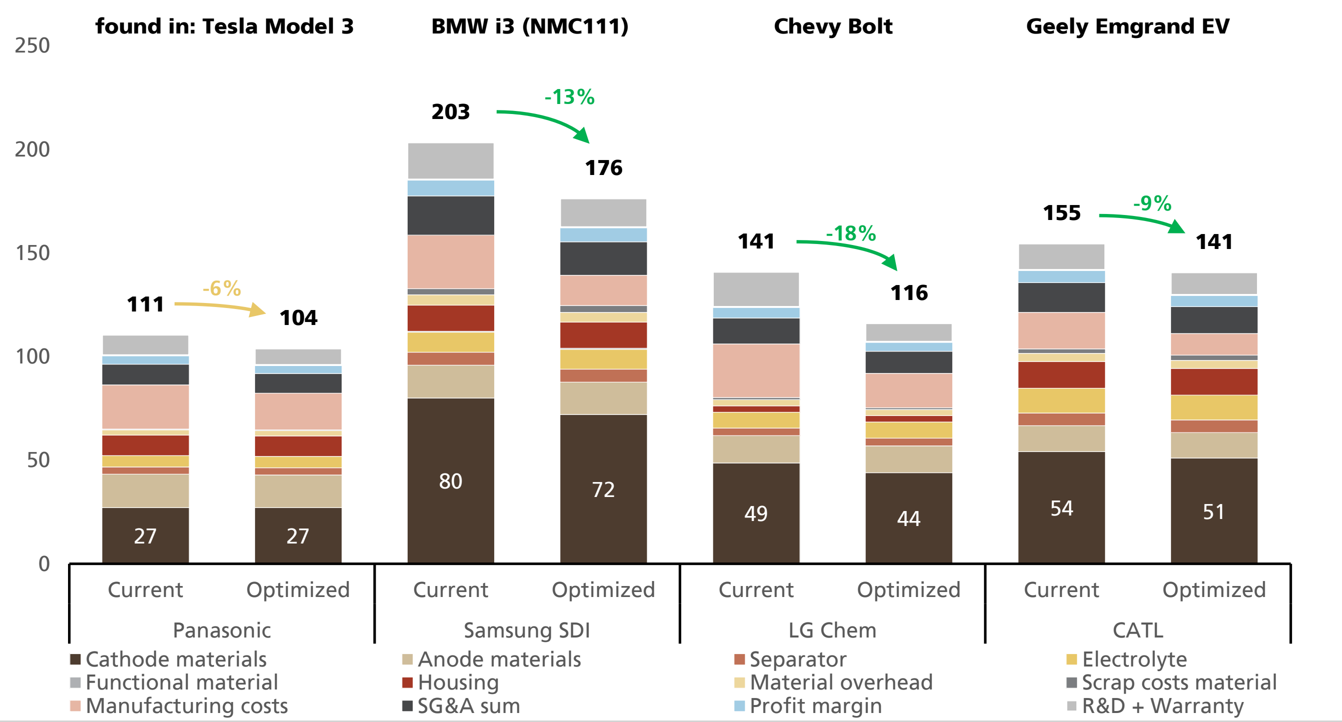


Source: UBS estimates based on Tesla Model 3

Key surprise finding: Panasonic wins with a $30/kWh lead

Panasonic is the big winner with its cells produced in the Tesla Gigafactory. Our analysis shows total cell costs $111/kWh, more than 20% lower than those of second-placed LG Chem. The key reasons behind Panasonic's victory are: (1) the scale advantage of the Gigafactory; (2) the simplicity of the cylindrical cell manufacturing process; and (3) the lower cost of raw materials in the NCA cell. We do, however, expect the Gigafactory's cost lead to shrink to ~10% over the next 2-3 years as competitors are scaling up. A move of the competitors to the new NMC811 chemistry after 2020 could narrow the gap further, even though Panasonic and Tesla are unlikely to stand still. We think Samsung SDI, whose prismatic cell screens significantly more expensive than LG's pouch cell, has substantial cost reduction potential via taking out over-engineered safety content.

Figure 4: Battery cell cost today vs fully scaled up ($/kWh) – Panasonic holds a significant lead

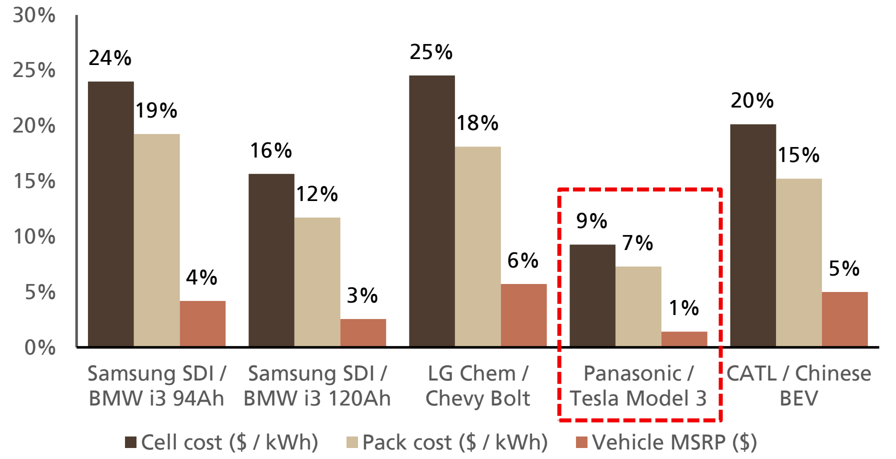


Source: UBS Evidence Lab Note: Optimized production scenario includes all benefits from economy of scale, but no change in energy density

We forecast Tesla/Panasonic to remain in the lead for as long as raw materials prices (cobalt in particular) do not collapse. If commodity prices increase further,

Tesla/Panasonic looks best protected, given its lower use of expensive cobalt. However, a rise in Nickel, which is highlighted as a likely scenario by the UBS commodity team, would affect Tesla/Panasonic slightly more than others given its nickel-intense cathode. Please see our interactive model for more details.

Figure 5: Tesla/Panasonic would be least affected if commodity prices increased (Scenario: 50% increase in price lithium, cobalt, nickel, manganese, aluminium)

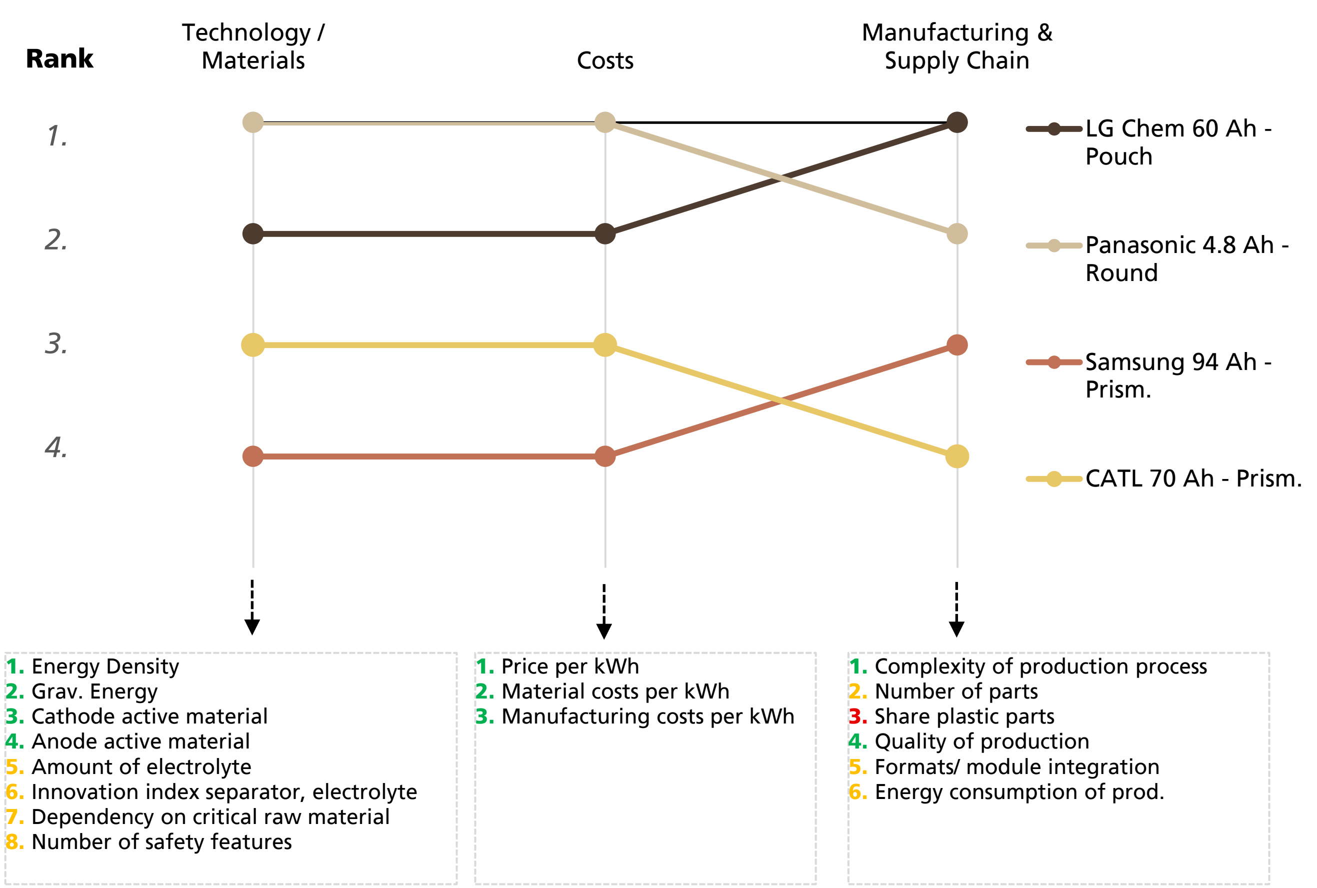


Source: UBS estimates [Note: MSRP = manufacturer's suggested retail price]

Panasonic and LG also win on other KPIs

However, cost per kWh is not the only metric that matters. The following overview summarizes the relative positioning of the four players in all key categories. **NCA** also wins in **volumetric energy density** (i.e., more range for the EV from a given size of battery tray), and uses the **lowest amount of critical raw materials**. It also has the **fewest components (8)** and the **least complex manufacturing process**. However, it has no innate safety features and requires a sophisticated battery management system (BMS), given the high number of cells (4,416 for the Model 3). Key advantages of **NMC pouch** cells include the **easier pack assembly** and the **better thermal stability**, reducing the cost of safety mechanisms and **requiring a less sophisticated battery management system (BMS)**. The **prismatic format (CATL and SDI)** has the **most components (up to 30)**, the **most complex manufacturing process** and the **lowest energy density**, but offers safety and packing advantages. The **pouch** format has the **highest gravimetric energy density (Wh/kg)**. Only 288 cells are required for the Chevy Bolt battery pack. This allows for a less specialized BMS, less connecting wires and greater safety. However, the pouch format also has a **complex stack and folding process** that requires additional manufacturing steps.

Figure 6: Cost/kWh is not the only thing that matters – battery KPI rankings at a glance



Source: UBS Evidence Lab
Note: Green colour indicates high relevance, red indicates lower relevance

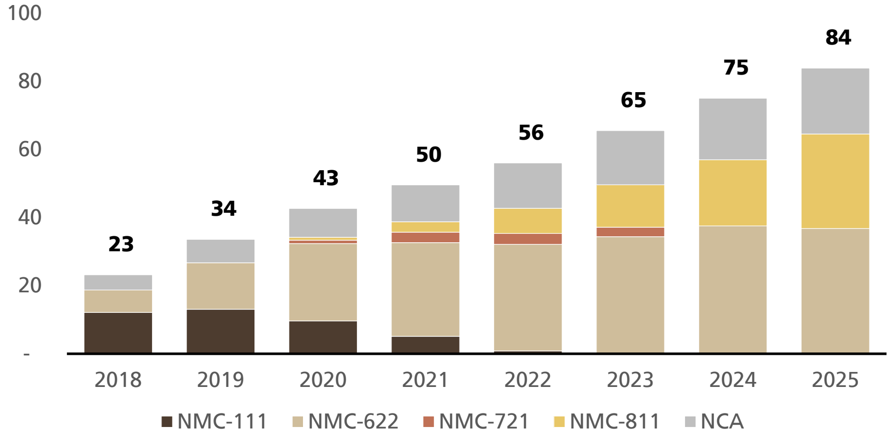
Global EV battery market to grow ~10x by 2025

EV battery revenues to $84bn by 2025, from $23bn today

Global EV battery demand will grow 9.5x, from ~93GWh in 2018e to ~973GWh in 2025e – the equivalent of 19 Gigafactories – while total battery demand grows almost six-fold to ~1,145GWh in 2025E from ~166GWh in 2018E. This is based on our EV sales forecast for 17.5m annual global sales in 2025 vs 1.8m this year, and results in a lithium-ion battery revenue pool of $84bn, up from $23bn today, which already reflects the anticipated price decline. In our bottom-up battery cell model, capacity growth modestly outpaces demand growth for the next three years. From 2022E, EV sales growth accelerates more quickly, needing investment above already ambitious plans to meet demand. Given a lead time of around three years for a new greenfield plant, this should not pose material risk of supply bottlenecks.

What is our EV sales forecast based on? We forecast 17.5m annual EV (battery electric + plug-in-hybrid) sales by 2025, up from 1.8m units this year. Our forecast is based primarily on our expectation for EV battery and non-battery powertrain cost reduction. On our numbers, EVs will achieve total-cost-of-ownership parity with internal combustion engine (ICE) cars in Europe this year, in China in 2023 and in the US in 2025. By then, we forecast EVs to be close to sticker-price parity with ICE cars in Europe.

Figure 7: Battery market opportunity ($bn)



Source: UBS estimates

Does Panasonic's cost lead mean the winner takes all?

Why Panasonic is winning but won't "take it all"

Does Panasonic's cost lead mean that incumbent OEMs will walk away from the Korean and Chinese suppliers? No. Tesla has created effective entry barriers that will likely prevent incumbent OEMs from switching their cell supplier: Panasonic's NCA cells are thermally less stable and need a very sophisticated battery management system (BMS) to control the temperature of each of the more than 4,000 cells in the Tesla Model 3. Only Tesla has over the years gained the know-how to create such a high-performing BMS. Incumbents would simply lose too much time in their EV launch strategies by switching to NCA. Further, the assembly of the battery pack is more complex for NCA because the number of cells is around ten times higher than in an NMC battery. Thanks to the Gigafactory, only Tesla has gained enough economies of scale to offset the disadvantage of a more complex pack assembly. Also, the cost difference between Panasonic and the Korean and Chinese players is likely to shrink as they scale up and move to NMC811 with a post-2020 view. Therefore, we expect most incumbents to consider NMC the better option for them long-term.

Several reasons why an oligopoly of the existing five leaders should persist

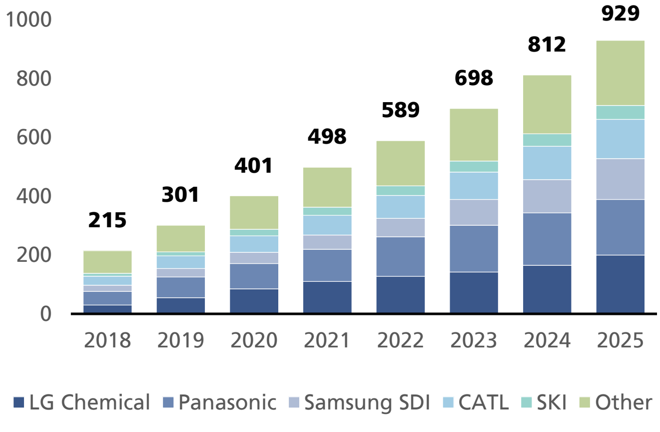
For carmakers, insourcing of battery cell production by the OEMs is *not* the answer, in our view, because the potential to catch up with the leading Asian players on the cost side is close to zero. A viable option, at least for the largest carmakers like Volkswagen, would be a joint battery plant investment with one of the leading existing cell producers (similar to the Tesla Gigafactory). This would enable the OEM to increase the stability of the supply chain, reduce logistics costs and exercise better control over raw materials. In our view, a critical mass of ~500k EV p.a. is required to justify such an investment.

Overall, we do not expect the competitive landscape for batteries to change significantly, as the likelihood of success for new entrants or other smaller players looks low absent an unexpected technological breakthrough. By 2021, we think the capacity of each of the top five producers will exceed 50GWh. We believe this implies almost insurmountable cost barriers for new entrants. With final investment decision (FID) today, they would likely be reaching commercial production merely for their first 2-5 GWh production line by then. We expect Panasonic, LG Chem, Samsung SDI, SK Innovation and CATL to still be sharing the global EV battery cell market on a 5- to 10-year view.

As the following charts show, cell capacity is likely to keep pace with growing demand over the next few years. Visibility on supply growth decreases after 2021, but we do not see cell capacity as a potential bottleneck. Our 2025 EV demand forecast would require the equivalent of 18 Gigafactories added globally.

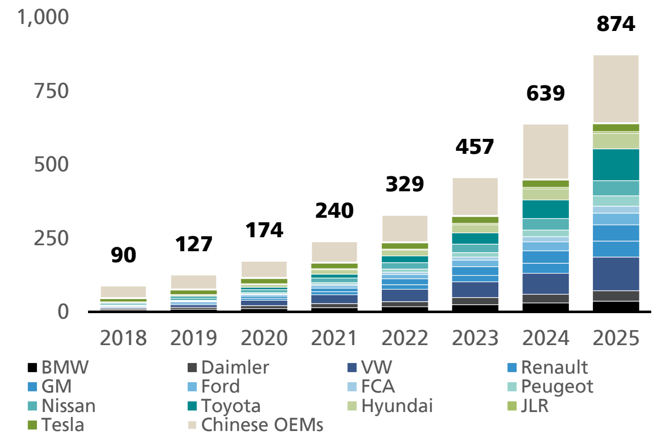
18 new Gigafactories needed

Figure 8: EV battery cell supply… (GWh)



Source: UBS estimates

Figure 9: …and demand by key players (GWh)

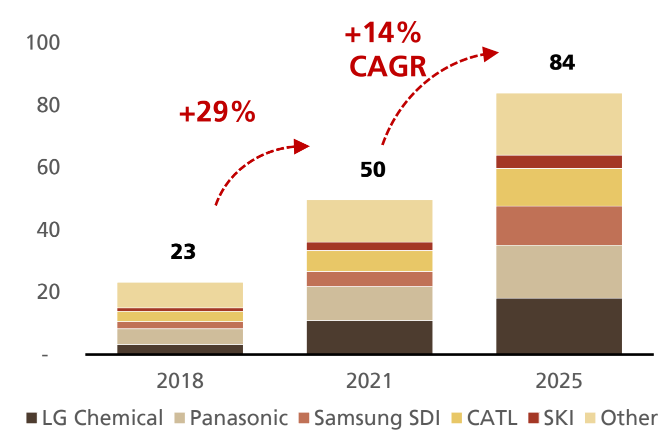


Source: UBS estimates

In spite of its cost leadership, Panasonic is likely to lose share to its competitors over the next few years, in our view, as neither global incumbents nor Chinese players are likely to switch to NCA chemistry (given the higher pack complexity and the more difficult thermal management). It is not even clear if Panasonic will fully track Tesla's growth path, as Tesla might partner with a local Chinese cell producer for its new Chinese car plant. We see LG as the biggest relative winner of market share.

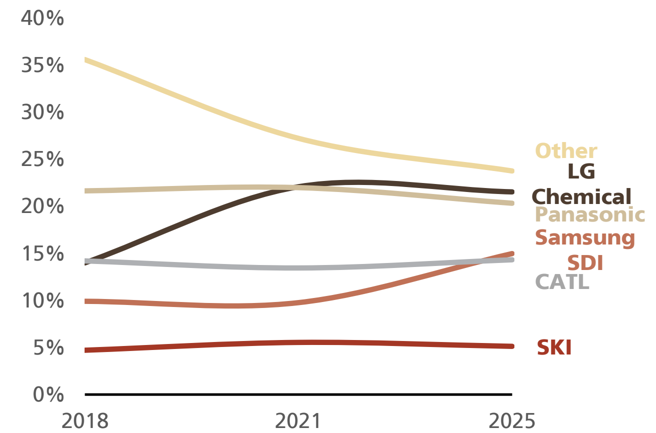
Panasonic is likely to lose share to its competitors while LG is likely to win

Figure 10: Battery revenue pool forecast ($bn)



Source: UBS estimates

Figure 11: UBS global battery market share forecast



Source: UBS estimates Note: Includes non-auto battery markets

Impact on auto industry: Tesla's battery cost edge over incumbent OEMs is bigger than we thought

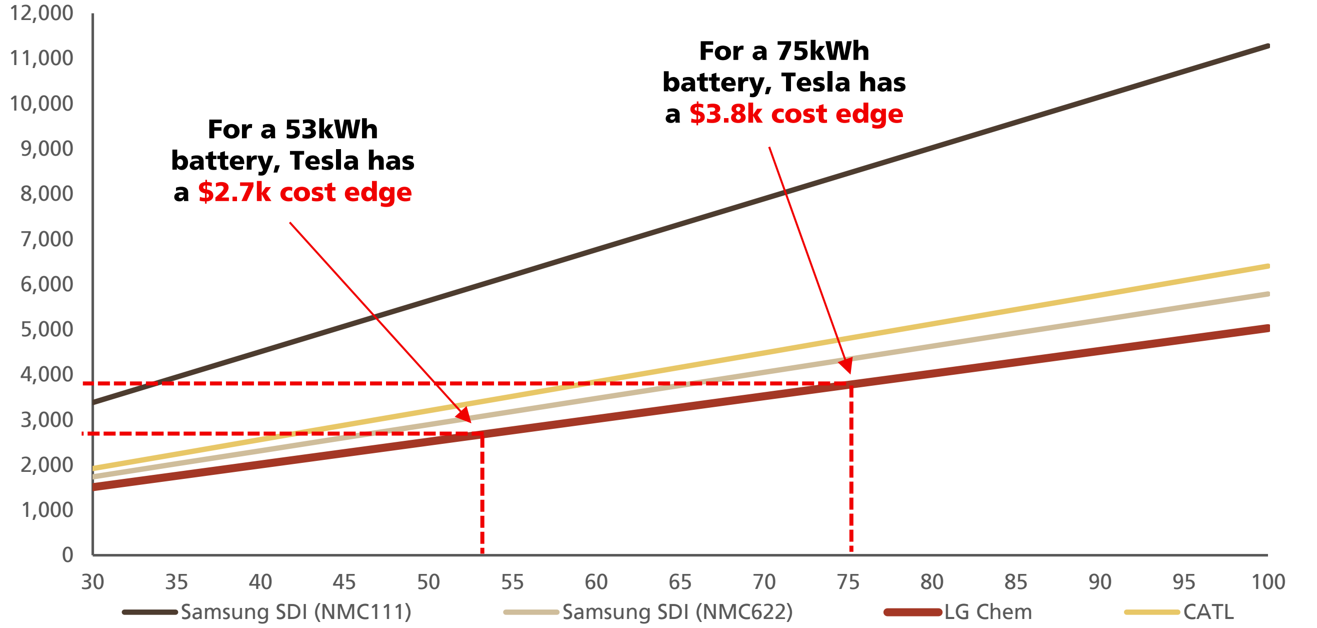
Tesla's cost lead over incumbents is bigger than we had assumed. On the $111/kWh Gigafactory cell cost, the 75kWh battery pack is ~$2,800 cheaper than outlined in our Model 3 teardown report. For the base version, which will likely have a ~53kWh battery, the difference is ~$2,000 per car. This is equivalent to a positive 2019E EBIT impact of ~$600m compared to our prior estimates.

Model 3 is ~$2-2.8k *cheaper than we had estimated* (equivalent to ~$600m more annual EBIT)…

Tesla's cell cost advantage over incumbents for the Model 3 (versus a generic incumbent EV with the same 75kWh battery pack) is ~$2,250 per vehicle, using second-placed LG Chem cells. On top of that, as the Model 3 teardown showed, Tesla has a ~$1,500 cost advantage over incumbents on the battery pack. This adds up to ~$3,750, or ~8% of the Model 3's selling price in the long-range rear-wheel drive (RWD) version we tore down. Therefore, we assume that premium incumbent OEMs will have a harder time competing with Tesla, resulting in a combination of lower sales and lower margins than we previously anticipated.

…and it has a $2.7-3.8k *cost advantage over EVs from incumbent OEMs*

Figure 12: Tesla's battery-related cost edge vs incumbents ($ per vehicle, kWh)



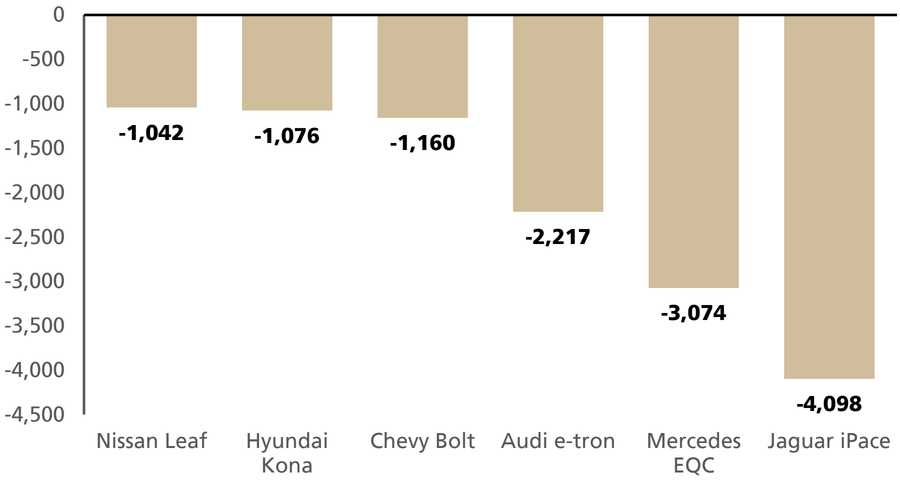
Source: UBS estimates

Other KPIs of the recently launched premium EVs from Mercedes, Audi and Jaguar also underscore Tesla's lead: the range per kWh and the battery weight per kWh, for example. These might influence consumer choices, because Tesla holds a lead in the overall range per charge and performance of the car. Another key edge is Tesla's battery-to-wheel efficiency (as a result of superior electronics), which translates into a **hard-dollar cost advantage of ~$1,000-4,000 per vehicle on top** of the above gap, because the incumbents have to use bigger (expensive) batteries to reach the same range as a Tesla, already adjusted for other factors such as weight, drag etc. We use a battery-to-wheel efficiency model to prove this. Should incumbent OEMs miss our expectations on volume, the lack of economies of scale would act as a drag on the EBIT margin trajectory over the next few years.

Tesla's electronics are the most efficient

On a positive note for the incumbents, the cost gap at the cell level should shrink to ~$900 per car once LG has reached full economies of scale, which would reduce the cost gap at a pack level to ~$1,700. The gap should narrow further with the arrival of the NMC811 chemistry around 2021/22, even though Panasonic and Tesla are also working on a further optimized NCA-based battery chemistry.

Figure 13: Tesla's leading battery-to-wheel efficiency gives the company an additional $1-4k cost edge over peers, on top of a lower battery cost per kWh



Source: UBS estimates

Battery cell teardown validates our EV thesis

~35% battery pack cost reduction potential by 2025

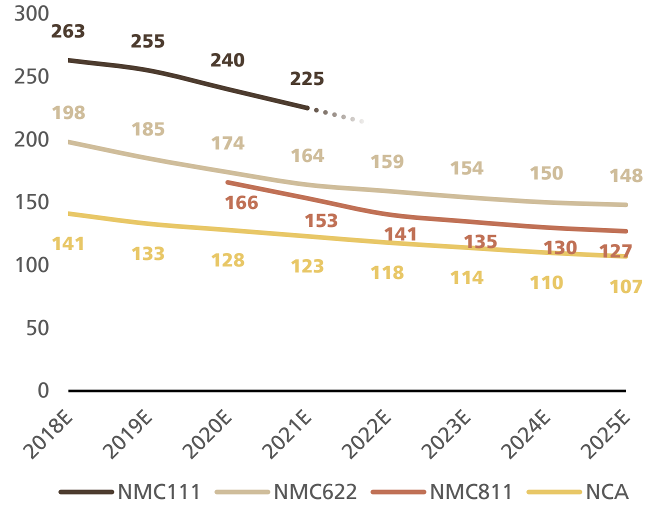
Another purpose of the cell teardown was to validate our battery cost forecast. Indeed, the $141/kWh cost for LG Chem's NMC622 cell – confirmed by the teardown – was almost bang in line with our expectations ($145/kWh). More importantly, the future areas of cost savings were also analysed in detail by the teardown engineers. These are mainly: (1) further economies of scale; (2) the gradual move to higher energy density and a lower-cost materials mix and (3) moving to cheaper locations from a manufacturing / supply chain perspective. For NMC622, the teardown revealed potential for a further 18% cost reduction to $116/kWh at full scale; for Tesla's NCA 2170, the teardown experts see 6% cost optimization potential (to $104/kWh) remaining. This lower delta can be explained by the much greater scale that the Gigafactory has already achieved today. There is additional cost reduction potential left for both chemistries. The step to NMC811, which would cut the cobalt content by almost half, will be a gradual process starting in the early 2020s, with the potential to reduce the cost per kWh by another ~15-20% versus NMC622. But the battery experts also see further optimization potential in cell chemistry and format for NCA.

Cell teardown experts do not foresee new technologies – such as solid-state batteries – entering the EV mass market before 2025

However, in line with our thinking, the cell teardown experts do not foresee new technologies – such as solid-state batteries – entering the EV mass market before 2025. Even thereafter, the commercial success of solid-state batteries remains highly uncertain, owing to technological challenges. Based on the findings from the cell teardown, we see another ~35% cost reduction potential on pack level by 2025 vs. today, which would bring EVs very close to sticker price parity vs. conventional cars. Our 2025 forecast is based on NMC811, which we expect to become mainstream in the early 2020s (slightly later than previously anticipated).

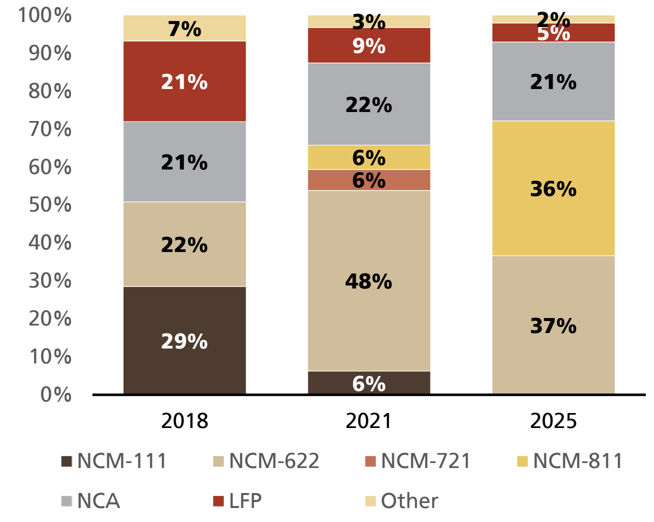
On this basis, we reiterate our forecast for 17m EVs to be sold annually in 2025, or 17% of global new car sales. We continue to see China and Europe as the regions with the steepest EV penetration curve.

Figure 14: UBS battery *pack* cost model ($/kWh)



Source: UBS estimates

Figure 15: EV battery chemistry mix



Source: UBS estimates Note: Includes non-automotive batteries

Implications for the global battery commodity markets

The battery teardown reinforces our forecast for a dramatic lift in EV sales towards 17.5m units annually by 2025E, or about 17% of annual global sales in that year, thanks to falling battery costs & improving performance, resulting in lower purchase costs & rising desirability. The key read through then for battery commodities is the increasing conviction in the EV battery revolution.

- **Lithium** markets are set to grow from **~265Kt LCE in 2018E to more than 1.15Mt LCE in 2025E**, a more than four-fold increase in market size. But lithium ain't lithium – we expect demand for high purity battery grade lithium hydroxide to grow fastest, in line with rising market share of both NMC & NCA batteries, and rising Ni intensity in NMC batteries. On the supply side, despite a deep inventory of lithium in mineral and brine resource, myriad challenges have kept the mooted 'wave of lithium' to more like a gradual rising tide, resulting in relatively shallow declines in world prices this year despite dramatic subsidy changes in China and strong growth in very low quality Chinese brine supply. **The outlook for prices is relatively more neutral than 12 months ago following lower prices through 2018.**

- **Nickel** demand into EV batteries is expected to lift **from ~60kt in 2018E to ~665kt in 2025E**, an eleven-fold lift that helps push nickel demand **from ~2.2Mt in 2018E to ~3.1Mt in 2025E**, as nickel-rich cathodes become the dominant chemistry for li-ion EV batteries, and as nickel loadings in those batteries lift too. The EV battery teardown and a lower Cobalt price have resulted in a slower rise of NMC-811 displacing lower Ni / higher Co NMC chemistries. On the supply side, the nickel industry is busy recalibrating upstream projects and midstream process flow sheets to lift output of nickel sulphate, the preferred form of nickel for cathode manufacture. Most new supply will likely come from laterite ores in Indonesia and/or the Philippines, either processed into nickel sulphate chemicals or nickel metal/matte via high-pressure acid leach (HPAL); or into nickel pig iron or ferronickel that is shipped to China before conversion into nickel sulphate at plants integrated with cathode manufacture. Key here is production costs of these routes. Debate continues on these figures, but even with aggressive and innovative Chinese investment, **prices required to drive investment are likely higher than current spot.**

- **Cobalt** demand is revised modestly higher following recent falls in the cobalt price, results of the EV battery teardown and downward revisions to the pace and extent of NMC-811 penetration. Despite this, very strong growth in new mine supply in DRC still sees the cobalt market **remaining in surplus until 2022-23E**. Cobalt demand is now expected to lift from 120Kt in 2018e to 260Kt in 2025e.

Impact on sector and company level

Global Autos

Sector Impact: Tesla emerges as the relative winner on the new evidence gained from the cell teardown. This is, relatively speaking, negative news for incumbent (premium) OEMs as Tesla could push more aggressively for a higher market share. As a consequence, EV margins and volumes of incumbents could remain lower than expected by consensus. However, in absolute terms, our EV cost estimates using NMC batteries have not changed, and the long-term cost trajectory for EVs overall remains favourable, ie, cost parity vs. ICE cars is likely to be reached around 2025, on our maths.

Most favoured names on the theme: *Volkswagen, Tesla (but already priced in), SAIC*

Least favoured name on the theme: *Faurecia*

Battery cell makers

Sector Impact: We view the battery cell makers as being one of the key beneficiaries in shift towards EV. We expect the industry to be an oligopoly dominated by the top 4 battery suppliers, who will have 71% market share by 2025. Incumbent players' cost will come down significantly as volume increase 2-3x. Absent a technological breakthrough the cost disadvantage for new entrants may prove insurmountable. In a highly concentrated market with the demand growing at 40% CAGR to 2025, we believe low single digit margin expectations currently priced-in are unrealistic.

The tear-down clearly shows cost savings that will come with scale and relocating production to lower cost locales. If we include a shift to higher energy density chemistries in the analysis then most players should reach the target of cell cost moving towards US$100/kWh by 2020/21. This increases our confidence on 1) Global EV penetration/EV battery demand, 2) company margin targets that are based on this level of cell cost and 3) high barrier to entry for players that lack scale.

Most favoured names on the theme: *LG Chem, Samsung SDI, Panasonic, CATL (but already priced in)*

Least favoured names on the theme: *Guoxuan High-Tech*

Chemicals

Sector Impact: There should be significant positives for battery producers and material suppliers such as Albemarle, LG Chem, Asahi Kasei, Umicore. On the flip side, disruption will likely be most evident among the autocatalysts producers BASF, Johnson Matthey and Umicore. The UBS view for EVs would lead to such material sales' loss that it would likely outweigh the positive impact of ongoing

legislation tightening for gasoline/diesel engines, especially in China. Over the long-term all three autocatalyst producers will look to exploit their OEM network to scale up their battery material businesses but for the moment Umicore is by far the leader of the three, as judged by order book and planned capacity. It is plausible, though, especially in the premium end of the auto market, that content growth for polymer and adhesives companies is significant (given a greater necessity for soundproofing and non-metal bonding). Finally we have to consider the modest long-term risk from peak gasoline/diesel arguments to future hydrogen growth in the industrial gases industry and weaker volumes in process catalysts (Clariant, W.R. Grace, Johnson Matthey).

Most favoured names on the theme: *Albemarle, Umicore, Asahi Kasei*

Least favoured names on the theme: *Johnson Matthey, EMS-Chemie*

Recent flagship research published on this topic

China Autos: Tesla Teardown: can Chinese OEMs compete with Tesla? – 10/2018

Q-Series - Tesla Teardown: Model 3 won the Race, but will it win the Championship? – 9/2018

Semis: Who's powering Tesla's Model 3? - Lap 2: Electronics - Driving with >$1,500 of semis – 8/2018

Semis: Who's powering Tesla's Model 3? - Lap 1: Powertrain - Some SiC(k) New Materials – 8/2018

Is Tesla Revolutionary or Evolutionary? - Lap 3: Fit and Finish – 8/2018

Is Tesla Revolutionary or Evolutionary? - Lap 2: Electronics – 8/2018

Is Tesla Revolutionary or Evolutionary? - Lap 1: Powertrain – 8/2018

Global Autos: Feedback from Asia Auto/EV/AV trip – 6/2018

Q-Series: Who will win the race to autonomous cars? – 5/2018

China Auto Sector: Where are Chinese companies in the race for autonomous vehicles? – 5/2018

Global Autos: Feedback from exclusive German electric car trip – 3/2018

China Autos "UBS Evidence Lab: Chinese brands' leading role ... [Erratum]" - 1/2018

Global Autos / UBS Evidence Lab - Electric cars: Highway to Margin Hell? – 11/2017

Q-Series: How disruptive will a mass adoption of robotaxis be? – 9/2017

European Autos: UBS Evidence Lab: Why suppliers appear overvalued against OEMs – 9/2017

Q-Series: UBS Evidence Lab Electric Car Teardown – Disruption Ahead? – 5/2017

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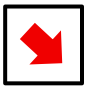
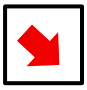
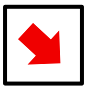
Near- and medium-term signposts

To test whether our thesis is playing out, this is what we'll be tracking in the upcoming months / quarters:

DATA RELEASE / EVENT DATE		WHAT WE EXPECT
Q4/2018	**China 2019 EV subsidy standard revision announcement**	**Potential indication of China opening market to foreign battery makers** The Chinese government will announce revised EV subsidy plans for 2019. Depending on the direction of the revision, we could see an impact on China EV volumes as well as domestic/foreign battery cell makers' market outlook. Our base case is foreign battery makers re-entering China once the subsidy expires in 2020, but any changes in the announcement could move the timeline in either direction.
H2/2019	**Porsche Taycan / VW I.D. launch**	**Evidence whether these key incumbent launches can catch up with Tesla** Porsche is expected to become the performance EV leader and the VW I.D. to become the most affordable mass-market EV below €30k (reaching six-digit unit sales territory in 2020). Should these models not meet expectations in terms of range, cost, performance, etc., that would further underscore Tesla's lead.
2020	**Tesla's China factory starts production**	**Significant price cut of Tesla Model 3 in China** Tesla's China factory could not only help it save tariff cost (40% currently, 15% if trade war ends), but also save $2K direct labour cost, whole car shipping cost, and some bill of material cost if they source locally. This would bring down Tesla's price tag from currently RMB1m for Model S/X to Rmb300K for the Model 3, and its addressable market size in China is going to expand from some 200K to 2m p.a.
2020/21	**China EV market re-entry with expected subsidy expiration**	**Opening of China's EV market to foreign battery makers** Foreign battery makers are currently excluded from the Chinese EV subsidy list, which has served as a significant entry barrier. With Chinese EV subsidies coming to an end by then, we expect to see foreign battery makers re-entering China. LG Chem has recently announced plans to add more capacity to its Chinese plant, and Samsung SDI as also noted the level of interest and engagement picking up.
2020/21	**Panasonic supplying Toyota for EV battery**	**New cell supply announcement(s) for Panasonic as a positive** While Panasonic currently only supplies Tesla, it would be a strong positive factor for Panasonic if it started to supply battery cells to other major OEMs such as Toyota. We think Toyota is the most likely candidate with on-going negotiations, but the timing remains unclear for now.
2021/22	**Battery cell cost reaching US$100/kWh**	**NCA and NMC811 cell costs to drop to (below) $100/kWh after 2020** We think the industry can achieve cell price of $100/kWh by 2021/22. We expect the cost reduction to be mainly driven by 1) chemistry shift from current NMC111/622 to NMC811; 2) lower fixed cost in R&D, SG&A and manufacturing with scale; and 3) location shift to lower cost regions like China.
Ongoing	**Tesla quarterly reports**	**Expect margin pressure as base configuration becomes available** We estimate contribution margins on Model 3 options average ~65%; therefore, we expect Tesla gross margins to fall from the 25.5% reported in Q3 once the base model becomes available for configuration. We are also forecasting a slower production ramp than consensus. We monitor Model 3 pricing, margins, and the production ramp quarterly.

Sector Thesis Maps

Global Autos

EV impact on sector … **Growth:**  **Margins:**  **ROIC:**  **Valuation:** 

KEY FINDINGS

Q: What did we learn from the battery cell teardown?
Tesla's lead is bigger than we had thought. Its battery pack costs are ~$2,250 lower per vehicle than for global incumbent OEMs. On top, Tesla's best-in-class battery-to-wheel efficiency saves another $1-4k per car.

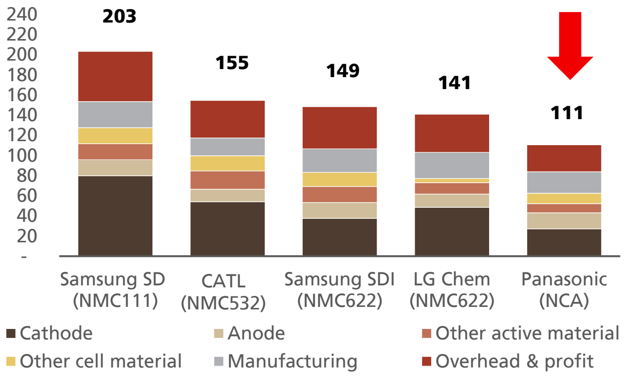
Q: What was the most non-consensual finding for the sector?
Tesla's cost lead is not consensual. The battery-to-wheel efficiency is completely overlooked by consensus so far.

FINANCIAL IMPACT

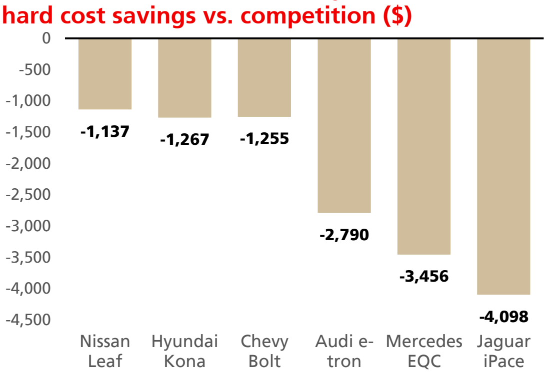
Q: What will be the financial impact of the key findings on the industry?
What is good news for Tesla is bad news for (premium) incumbents, because it will be more difficult for them to sell EVs profitably in competition to Tesla. Tesla's lead could also be bad news for tier-1 suppliers, as their EV content growth story stalls. Tesla has the highest degree of in-house manufacturing of the electric powertrain.

Source for charts: UBS Evidence Lab, UBS estimates

Tesla's cost lead on battery pack level ($/kWh)



Tesla's best-in-class efficiency translates into hard cost savings vs. competition ($)



SECTOR HEALTH CHECK

Q: In light of the key findings in this report, how well is the sector prepared if our thesis plays out?
Semi-prepared. While most legacy OEMs and suppliers are working hard on the transition to EVs, Tesla's undeniable lead and the emergence of Chinese EV producers poses a threat to margins and returns.

SECTOR VALUATION

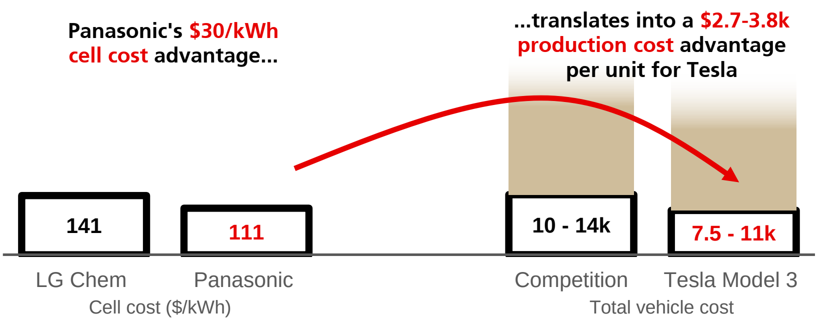
Q: Will our findings in this report lead to a change in sector valuation multiples? Is consensus too positive or too negative on the theme?
Multiples have already contracted and are ~30% below mid-cycle. We are relatively more cautious on tier-1 suppliers for which consensus still seems too optimistic on the EV (and AV) content growth story.

STOCK IMPACT

Q: What stocks will be impacted most positively and negatively in the sector?
Tesla emerges as the relative winner on the new evidence gained from the cell teardown. This is, relatively speaking, negative news for incumbent (premium) OEMs as Tesla could push more aggressively for a higher market share. However, some traditional OEMs are well-positioned to compete with Tesla and become EV-leaders: Volkswagen sticks out most positively on scale benefits and its particularly aggressive strategy. Amongst suppliers, those with a skew to ICE powertrain are worst positioned.

NEED TO KNOW

Q: What else should investors know? - Panasonic's cell ($/kWh) and Tesla's vehicle cost advantage ($)



Source for 3 charts on this page: UBS Evidence Lab, UBS Note: $2.7-3.8k range in above chart reflects different battery size versions of Model 3

MOST FAVOURED ON THIS THEME	Stock	UBS rating	2019E PE	EPS impact from EV 2025E	Comment
	Volkswagen	Buy	5x	10-25%	Can become global #1 EV producer
	Tesla	Sell	-	>100%	Currently leading in EV technology, although already priced in
	SAIC	Buy	8x	10-25%	Leading EV producer in China

LEAST FAVOURED ON THIS THEME	Stock	UBS rating	2019E PE	EPS impact from EV 2025E	Comment
	Garrett Motion	Sell	3.5x	<1%	Almost no pure BEV content today
	Faurecia	Neutral	9x	0%	Leading PV ICE exhaust systems player

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Batteries

EV impact on sector ... **Growth:** ↗ **Margins:** ↗ **ROIC:** ↗ **Valuation:** ↗

KEY FINDINGS

Q: What did we learn from the battery cell teardown?
Panasonic /Tesla has a ~20% cost lead versus LG Chemical, Samsung SDI and CATL. However, that lead will likely narrow down to ~15% as Panasonic competitors scale up and optimize production.

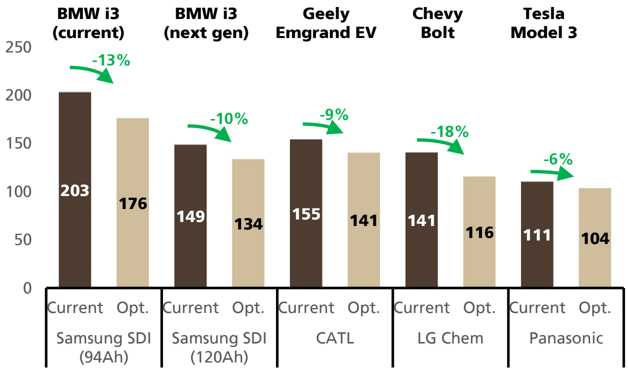
Q: What was the most non-consensual finding for the sector?
Despite Panasonic's cost advantage we expect to see limited adoption by other OEMs. A sophisticated battery management system (Tesla produces in-house) is required for the format and we do not think this is easily replicable. CATL's cell compares favorably to foreign players on a number of KPIs. We believe new entrants will struggle to catch up to incumbents and see the bulk of global share going to five players. We believe CATL and LG Chem will gain more market share into 2025.

FINANCIAL IMPACT

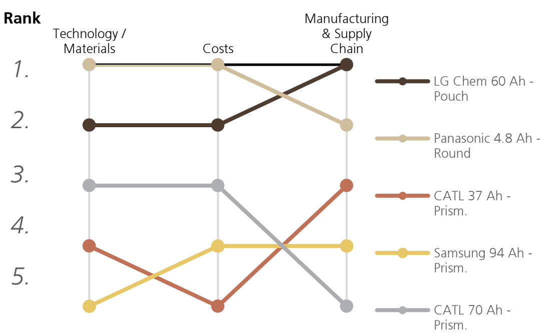
Q: What will be the financial impact of the key findings on the industry?
We expect EV battery industry revenue CAGR to 2025 of 23%.

Source for charts: UBS Evidence Lab, UBS estimates

Battery cell cost today vs. fully scaled up [US$/kWh]



Battery KPI ranking at a glance



SECTOR HEALTH CHECK

Q: In light of the key findings in this report, how well is the sector prepared if our thesis plays out?
We believe that new entrants face insurmountable barriers to entry. We expect the industry to become a five player oligopoly. In terms of capacity expansion plans we believe leading battery makers can meet demand.

SECTOR VALUATION

Q: Will our findings in this report lead to a change in sector valuation multiples? Is consensus too positive or too negative on the theme?
Consensus vastly underestimates barrier to entry for new entrants. Given our view of an oligopoly structure for the industry we believe consensus expectations of low-to-mid single digit operating margins for battery makers are too low. We also believe consensus underestimates the potential for battery costs to come down through scale and optimized production. It is likely that near-term earnings growth potential is also underestimated.

STOCK IMPACT

Q: What stocks will be impacted most positively and negatively in the sector?
Positively impacted stocks in order of preference are LG Chemical, Samsung SDI, SK Innovation and Panasonic. Players that are struggling to make the shift to high energy density chemistries such as Guoxuan High-Tech are unlikely to find short-term solution to make the technology leap and earnings could continue to disappoint.

MOST FAVOURED ON THIS THEME

Stock	UBS rating	2019E PE	EPS impact from EV 2025E	Comment
LG Chem	Buy	9x	25-50%	Targeting 100GWh capacity by '21E
Samsung SDI	Buy	13x	25-50%	Large Batteries (EV + ESS) to generate ~50% of revenue and ~40% of OP by '22E
Panasonic	Neutral	12x	10-15%	Teardown shows lead in tech and cost. Supplying to Toyota could be upside

LEAST FAVOURED ON THIS THEME

Stock	UBS rating	2019E PE	EPS impact from EV 2025E	Comment
CATL	Sell	42x	>50%	Undisputed national champion, but valuation rich and margins too high to sustain especially after market opening-up
Guoxuan Hi-Tech	Sell	24x	25-50%	Persisting risks in shifting from LFP to NMC and to higher energy density

NEED TO KNOW

Q: What else should investors know?
At this stage we do not see particular battery cell format (cylindrical, prismatic or pouch) as becoming the industry standard. Each format has its pros and cons.

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Chemicals

EV impact on sector ... **Growth:** **Margins:** **ROIC:** **Valuation:**

KEY FINDINGS

Q: What did we learn from the battery cell teardown?
The teardown work shows that improvements in better manufacturing and moving to higher nickel content batteries (eg. 811NMC and silicon based anodes) will be key to driving down cost per GWh of batteries. This should benefit those battery component companies that already have commercial products and have the ability to work with battery manufacturers to drive down costs. This could provide a barrier to entry for new entrants.

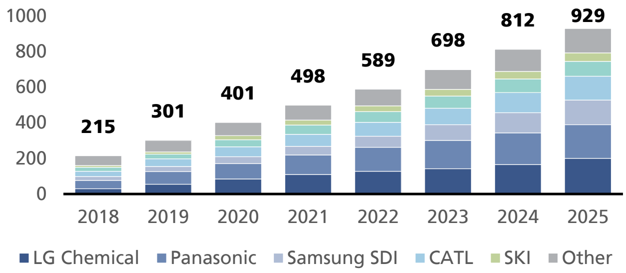
Q: What was the most non-consensual finding for the sector?
Consensus modelling for EV penetration by 2025 is in the range 10-15%. Our global estimate of 17% is clearly well above this consensus base case and would likely differ from chemicals companies' planning scenarios.

FINANCIAL IMPACT

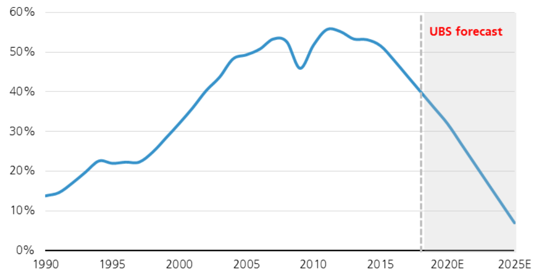
Q: What will be the financial impact of the key findings on the industry?
A wide range of impacts. There should be significant positives for battery producers and material suppliers such as Albemarle, LG Chem, Asahi Kasei, Umicore. On the flip side, disruption will likely be most evident among the auto catalysts producers BASF, Johnson Matthey and Umicore. The UBS view for EVs would lead to such material sales' loss that it would likely outweigh the positive impact of ongoing legislation tightening for gasoline/diesel engines. It is plausible, though, especially in the premium end of the auto market that content growth for polymer and adhesives companies is significant (given a greater necessity for soundproofing and non-metal bonding). Finally we have to consider the modest long-term risk from peak gasoline/diesel arguments to future hydrogen growth in the industrial gases industry and weaker volumes in process catalysts (Clariant, W.R. Grace, Johnson Matthey).

Source for charts: UBS estimates

Battery installation growth (GWh)



We still expect EU diesel mkt share to collapse



SECTOR HEALTH CHECK

Q: In light of the key findings in this report, how well is the sector prepared if our thesis plays out?
Yes but not likely at the pace we suggest. Management, no doubt, will be planning strategies around powertrain scenarios. Perhaps, though, none expect a '1 in 3 world' for European EV penetration by mid next decade.

SECTOR VALUATION

Q: Will our findings in this report lead to a change in sector valuation multiples? Is consensus too positive or too negative on the theme?
We have already seen a major shift in valuations (eg Umicore's re-rating) related to EV growth prospects. Tough to generalise overall but for the most part the impact on the Chemicals sector will be moderate given the size in market cap terms of stocks that are less impacted by the theme e.g. the heavyweight conglomerates (BASF, DWDP), Gases (PX, LIN, AI, APD), Coatings (AKZA, PPF, SHW, AXTA), and Agriculture (CF, ICL, MOS, NTR, OCI, PHOR, SDF, YAR etc).

STOCK IMPACT

Q: What stocks will be impacted most positively and negatively in the sector?
We are Buy-rated Albermarle, Asahi Kasei, LG Chem and Victrex partly related to EV vehicle growth opportunities in EVs. Umicore's growth ambitions are impressive but, we argue, are broadly discounted now. We do not believe that the valuations of EMS Chemie or Johnson Matthey capture risks associated to their ICE-related assets.

MOST FAVOURED ON THIS THEME

Stock	UBS rating	2019E PE	EPS impact from EV 2025E	Comment
Albemarle	Buy	16.6x	25-50%	We estimate that 30% of 2018e EBITDA could be battery-grade lithium
Umicore	Neutral	23.6x	25-50%	First mover advantage in battery materials but growth potential broadly discounted
Asahi Kasei	Buy	9.0x	10-20%	The top player in battery separator industry where the entry barrier is relatively high

LEAST FAVOURED ON THIS THEME

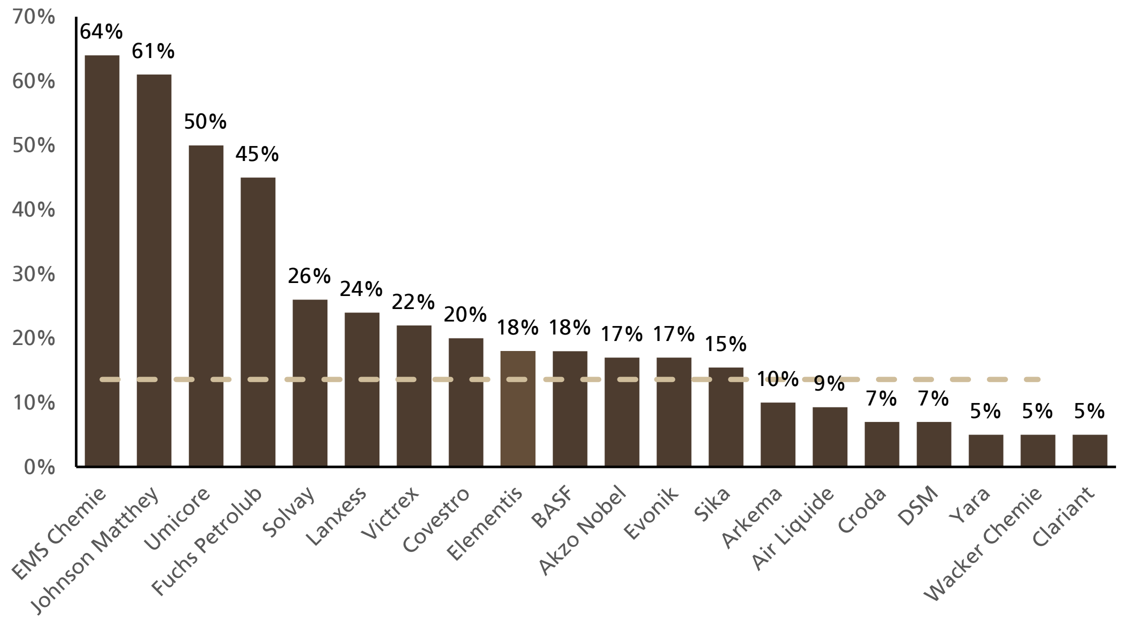
Stock	UBS rating	2019E PE	EPS impact from EV 2025E	Comment
Johnson Matthey	Sell	12.9x	10-20%	The biggest net impact due to exposure to light duty diesel (16% of EBIT) and PGMs & only modest position in battery materials
EMS-Chemie	Sell	24.3x	5-10%	Valuation too rich. Uncertainty on polyamide loadings in EVs versus ICE but hybrid migration may help in the interim

NEED TO KNOW

Q: What else should investors know? / the sector impact in more detail

Autos is one of the key end-markets for the Chemicals industry (we estimate around 14% of the sector's revenues directly but up to 20% of revenues indirectly, i.e. to products that ultimately end up on a vehicle). As a consequence this will be a major theme for the industry but we will most likely see positives and negatives counterbalancing each other. Higher content growth for polymers may well continue in both OEM production and EV infrastructure. Conversely, lower demand for components for the combustion engine such as autocatalysts and certain engineering plastics will undoubtedly ensue. The less straightforward analysis is on the energy supply chain overall considering that there may well be bottlenecks in the pace of EV infrastructure build-out. We capture these risks in our downside scenarios. Of course from a European perspective at least there is a significant component of the SX4P that has little or no exposure to autos at all and we would estimate this at around 35-40% of the sector (Consumer Ingredients, Fertilisers, Kemira, Lonza & Akzo Nobel).

Transport (mainly passenger cars) exposure of EU Chemicals *(source: UBS estimates)*



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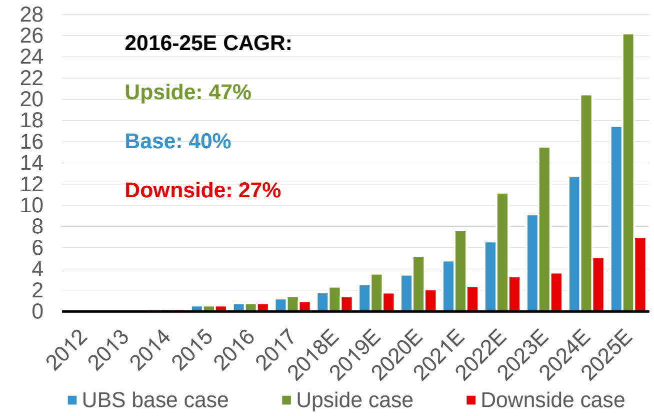
Cell analysis validates EV cost roadmap; Tesla's lead is bigger than expected

NMC in line with expectations, but Gigafactory surprises

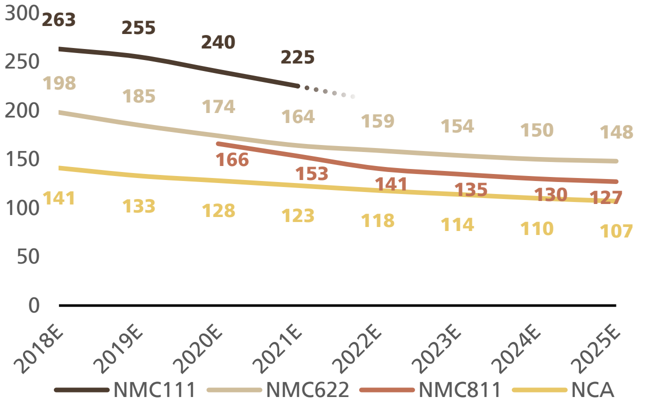
NMC 622 costs of $141/kWh for the cell supplied by LG Chem are almost bang in line with the $145/kWh we estimated on the back of the Chevy Bolt teardown that UBS Evidence Lab conducted back in 2017. As we used this cell type as our industry benchmark, we can reiterate our industry forecasts for: (1) global EV sales penetration; and (2) the NMC battery price trajectory between now and 2025. Based on the data from our cell teardown, we consider an NMC811 cell price of ~$90/kWh as achievable by 2025 (at constant commodities). On a pack level, this should translate into ~$120/kWh (the $30/kWh for the pack is achieved by Tesla in the Gigafactory already today), compared with ~$190/kWh today. The annual cost decline should be in the 6-7% range. At this pace, sticker price parity relative to an internal combustion engine (ICE) car would almost be reached by 2025. Tesla could reach this point before 2025, given its cost advantage.

Figure 16: UBS global EV sales forecast scenarios (m units)



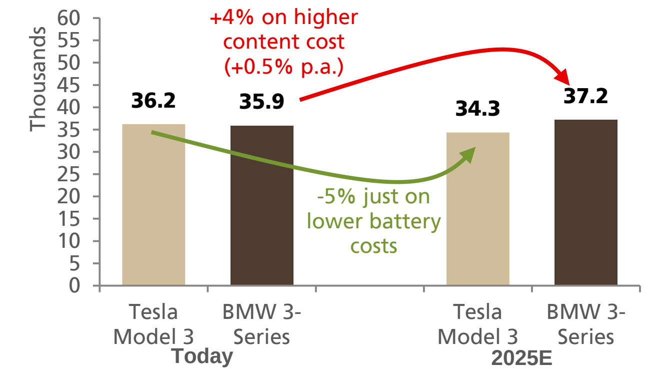
Source: UBS estimates

Figure 17: Battery *pack* cost trajectory ($/kWh)



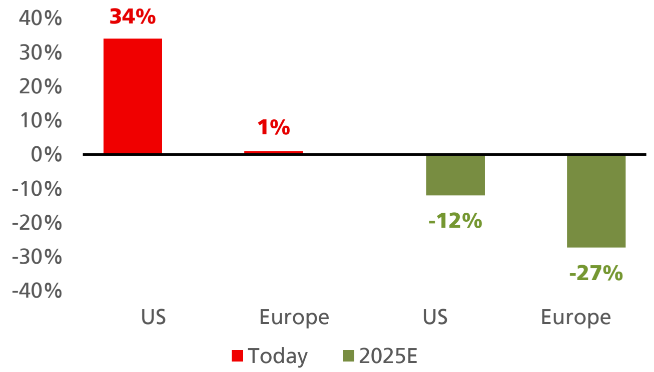
Source: UBS estimates

Figure 18: BEV vs. ICE vehicle price today and in 2025E (example Tesla Model 3 (short range) vs BMW 3-Series, $)



Source: Company data, UBS
Note: Based on $35,000 Model 3 base price + $1,2k destination fee and base BMW 3-Series price. 2025E Model 3 price based only on battery cost decline vs. today. 2025E BMW 3-Series price based on annual 0.5% content cost growth.

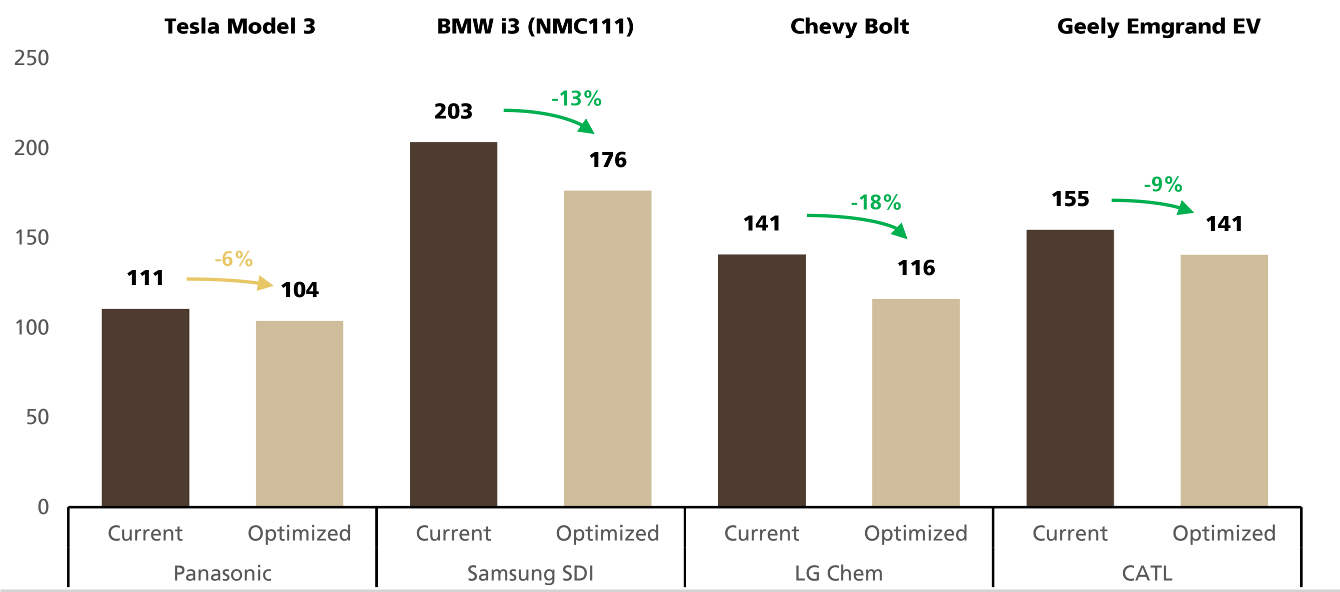
Figure 19: BEV vs ICE TCO today and in 2025E (example mass-market car, in %)



Source: UBS
Note: Derived from proprietary UBS TCO model (available in interactive format); based on three-year TCO (total cost of ownership) for Chevy Bolt EV and equivalent variant of VW Golf ICE car.

The key surprise finding is the substantial cost advantage of Tesla's Gigafactory. Compared to the initial estimate based on the Tesla Model 3 teardown, the cost per kWh turned out to be $37/kWh lower, or ~$2,800 per vehicle (long-range version). In other words, Tesla's lead over the competition is bigger than we had assumed, between ~$2,700 (base version) and ~$3,800 per vehicle (75kWh battery version) on the pack level. We believe this could give Tesla the opportunity to undercut the pricing of competitors and/or to make better margins than incumbents. As the detailed cell cost analysis has shown, LG, Samsung and CATL have more remaining cost reduction potential from economies of scale. However, it will likely take 2-3 more years before those levels are achieved – and even then, Tesla would be able to defend a lead by $12/kWh or ~$800 per vehicle on the cell level. The cost advantage in the pack assembly comes on top.

Figure 20: Tesla's (Panasonic's) cost lead over cells provided by competitors (75kWh battery) – based on current and optimized production set-ups

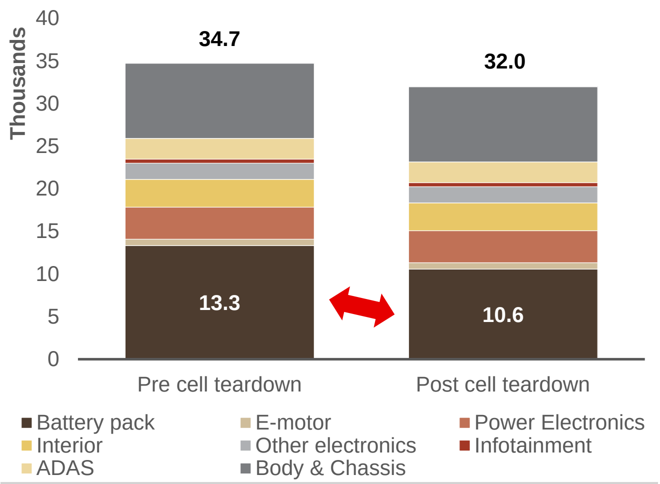


Source: UBS estimates Note: Optimized production scenario includes all benefits from economy of scale, but no change in energy density

Updated maths for Model 3: Battery is ~$2,800 cheaper to produce than expected

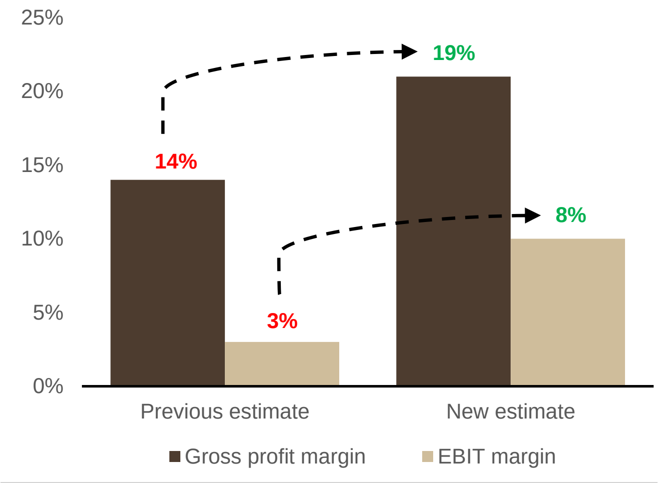
With its Q3 results, Tesla has shown that it can produce the Model 3 at a profit, in spite of an annualized production run-rate of only ~220k units/year. Of course, this was achieved with an ASP of $60k, which is unlikely to be sustainable as the lower-mix versions are being phased in. The following overview shows the cost structure of the Model 3 based on the UBS Evidence Lab teardown findings, updated for the battery costs from the cell teardown. Cell costs are ~$2,800 (75kWh version) lower than we previously assumed based on the Model 3 teardown. UBS Evidence Lab did not perform a teardown of the cell at the time of the Model 3 teardown.

Figure 21: We over-estimated Model 3 (75kWh version) costs by ~$2,800…



Source: UBS estimates

Figure 22: …and underestimated its EBIT margin (for a $45k version) by 5%-pts



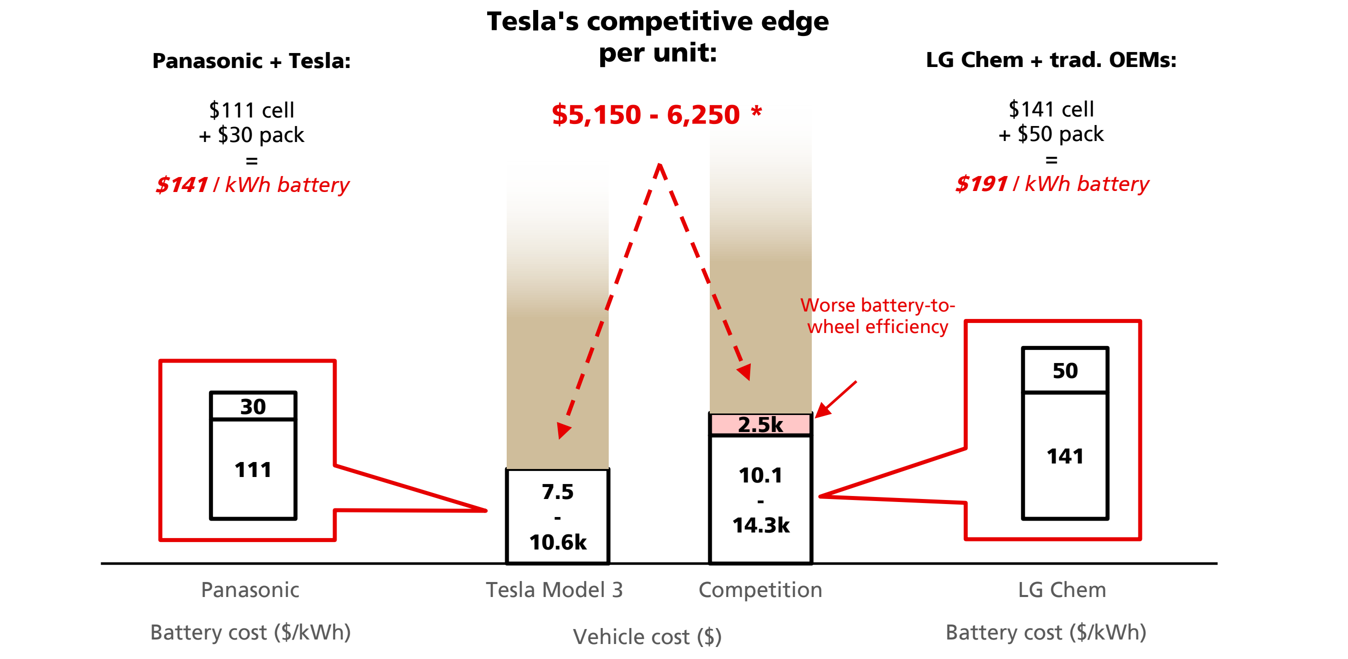
Source: UBS estimates

Based on the above updated cost structure, the break-even point for the Model 3 drops to $40k. On our estimated average transaction price (ATP) of $48.5k in 2019, Tesla makes a $3.8k operating profit per vehicle. This now means that Tesla is likely in positive earnings and FCF territory on a sustainable basis.

Wider-than-expected cost gap – Tesla edges away from incumbents

We see downside risk to our base case forecasts on the EU/US incumbent OEMs vs. Tesla on a relative basis. The areas of Tesla's competitive edge are (1) lower cell costs; (2) lower pack costs and (3) a BMS that effectively represents an entry barrier for incumbents to switch to NCA. We also did a deep-dive into the battery-to-wheel efficiency of various EV models with an unexpectedly clear outcome…

Figure 23: Cell cost, pack costs, battery-to-wheel efficiency – Tesla's edge vs. incumbents is bigger than expected



Source: UBS Evidence Lab * Range is based on 53kWh battery (short range Model 3) and 75kWh battery (long range)

- **Tesla's cell cost/kWh edge** is substantially larger than we previously estimated, meaning that incumbents will be less profitable than Tesla with their EV models. The finding also de-emphasizes our thesis that incumbents can undercut Tesla's pricing by leveraging firm-wide economies of scale.

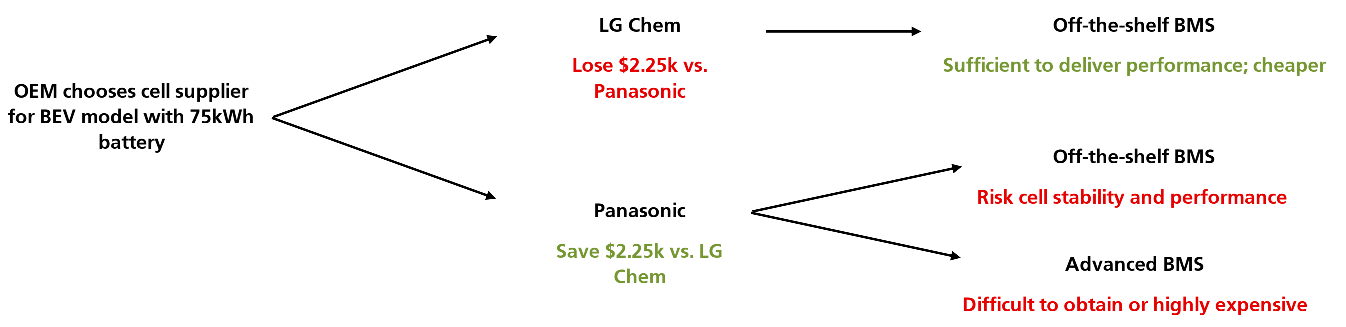
- **Battery pack costs are another of Tesla's assets.** Tesla's lean and sophisticated battery pack design was the key area of upside surprise during the cell teardown. With a pack cost of just $30/kWh, the Model 3 has set a new benchmark, well below the $60/kWh the teardown experts estimated for the Chevy Bolt. While there should be some cost digression on a per kWh basis for larger battery packs, we do not think the incumbent EVs launched recently have brought any further innovation to the table. While we expect incumbents to also reduce the gap via benchmarking versus Tesla, the basic layout of the latest product launches (the Audi e-tron, for example), is still relatively similar to that of the Chevy Bolt. Tesla is likely to be able to defend a $10-20/kWh cost lead per kWh on the module/pack level, in our view, resulting in an $800-1,600 cost advantage over premium competitor models.

- **Why will incumbents not simply buy the Panasonic cell if it is cheaper? The BMS creates an entry barrier.** Thanks to the millions of miles driven by Tesla owners globally feeding into Tesla's AI machine, we think Tesla has the best BMS available in the market, resulting in superior performance and battery life. Incumbent OEMs are unlikely to use the cost-leading Panasonic cell because it is much more difficult to balance several thousands of cells, and the risk of delivering substantially worse KPIs than Tesla on the Panasonic cells would be high. NCA is a less stable chemistry than NMC – that is, a well-functioning BMS is a prerequisite to prevent overheating (and the battery catching fire). We think incumbents are unlikely to take this safety risk, as it took Tesla years to minimize the risk of fire. So far, there are no known incidences with the Model 3. Tesla can thus capitalize on its cost lead with the Gigafactory, as its BMS has created substantial barriers for competitors to switch to NCA.

BMS creates an entry barrier to incumbents simply switching to the Panasonic cell

- **The Gigafactory turns out to be a strategic asset** rather than a highly capital-intensive burden on Tesla's returns and cash generation. It will take several years for incumbents to reach similar economies of scale. Further, regional proximity to the OEM assembly plant is also an asset as logistics costs for battery packs (and the tied-up working capital) are high. Large volume carmakers like VW will likely need to co-invest in a battery plant similar to the Gigafactory model, but they will be 4-5 years behind Tesla.

Figure 24: Why do incumbent OEMs not simply move to Panasonic if the cell is cheaper?



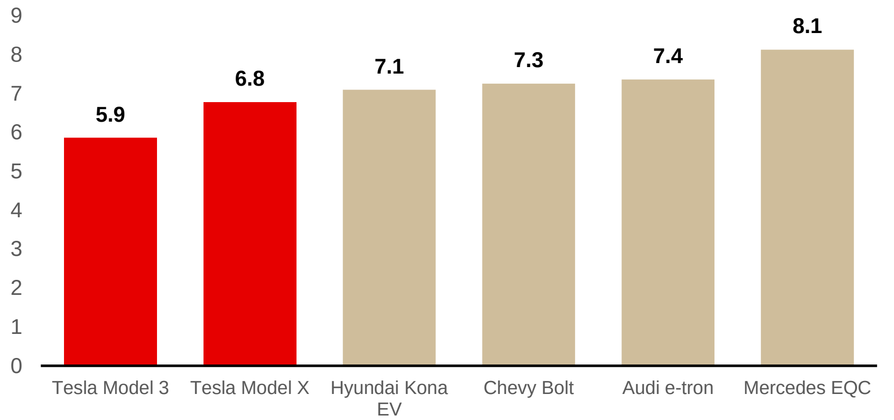
Source: UBS

Additional evidence for Tesla's lead

Moreover, the most recent launches from Mercedes (EQC) and Audi (e-tron), two of the long-awaited first "serious" responses by the German premium OEMs to Tesla, have shown that there are other important areas where Tesla has a wider-than-expected lead. Some aspects like the higher weight might be attributable to the fact that these models are not yet on dedicated EV platforms, but the drivetrain and the battery packaging should not be affected.

- **Battery capacity-to-weight:** Audi and Mercedes' battery packs are ~2kg/kWh heavier than the Model 3 pack. One cannot argue with crash safety, because the Model 3 received a 5-star NHTSA rating as the safest car ever tested. On a large battery of 90kWh, this adds up to a weight difference of almost 200kg, which adversely affects range, acceleration and handling.

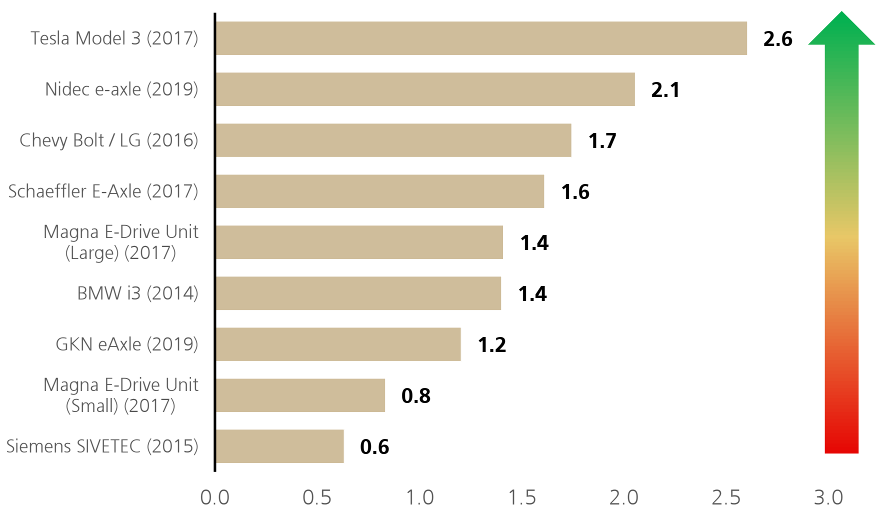
Figure 25: Battery pack weight vs capacity (kg per kWh)



Source: Company information, UBS Evidence Lab

- **E-drivetrain:** We found that Tesla's Model 3 has the best power-to-weight ratio of its electric drive unit (motor and gearbox) of any electric vehicle in the market.

Figure 26: Power-to-weight ratios of commercially available electric drivetrains



Source: Company information, UBS

Measuring Tesla's lead – the Model 3 has the highest battery-to-wheel efficiency

Optimizing the range per kWh battery capacity is very important for the OEM, because, the battery is the most expensive part in an EV. The "conventional" ways to increase the range per kWh is to design an EV with excellent aerodynamics and/or low weight. As shown above, Tesla takes a leading role on the weight side. Another aspect often overlooked and not well understood is the efficiency of the electronics in the car. We have developed a model that analyses the efficiency of the electric powertrain of any EV. In simple terms, the efficiency ratio shows how many electrons pumped by the charger into the battery will ultimately translate into the acceleration of the car. Efficiency losses occur in the **on-board charger**, the **cabling**, the **inverter**, the **e-motor** and the **gearbox**.

To derive this efficiency ratio, we take the measured EPA range and the battery size of a specific EV as an input into a complex formula known academically as a standard dynamic vehicle model. This model takes into consideration the impact of the vehicle form factor, the weight, the wheel size, etc. – all of which have an impact on the vehicle's range. The output is the battery-to-wheel efficiency. The higher the ratio, the better the job done by the OEM.

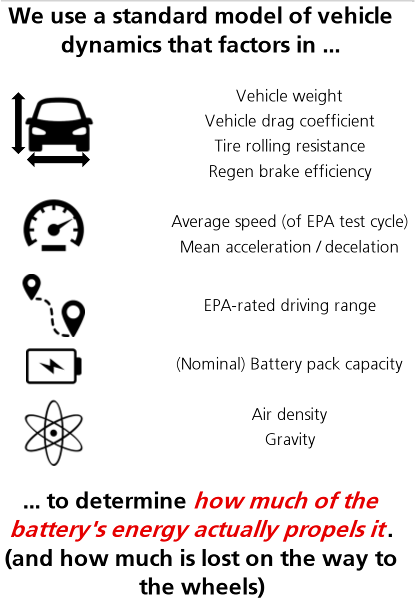
How does this formula work?

There are four different areas of resistance that determine the energy consumption of any car: **(1) drag, (2) rolling resistance, (3) topography and (4) internal efficiency** of the car. There are several ways to increase the range of an EV with the least amount of battery capacity required:

- **Reducing the weight (affects 2 and 3).** Batteries with a high energy density, and/or a sophisticated battery pack design help to reduce the weight.
- **Improving the aerodynamics (affects 1).** A low drag coefficient is an important metric to look at when comparing different EVs in the same segment.
- **Using the most efficient power electronics (affects 4).** This aspect can also be called "battery-to-wheel" efficiency. The higher the ratio, the less energy gets lost on its way from the battery to the wheels of the car.

All of the above can be reflected in this "monster" formula:

Figure 27: How do we estimate battery-to-wheel efficiency?



Source: UBS

Figure 28: We use a standard dynamic vehicle model to determine the battery-to-wheel efficiency of electric cars

$$E_p = \left[\frac{\left(\frac{1}{2}\rho \cdot C_d \cdot A \cdot v_{rms}^3 + C_{rr} \cdot W_T \cdot g \cdot v + t_f \cdot W_T \cdot g \cdot v \cdot Z\right)}{n_{bw}} + \frac{1}{2} W_t \cdot v \cdot a \left(\frac{1}{\eta_{bw}} - \eta_{bw} \cdot \eta_{brk}\right) \right] \left(\frac{D}{v}\right)$$

$\rho = Density\ of\ air\ \left(\frac{kg}{m^3}\right)$

$g = Gravity\ \left(\frac{m}{s^2}\right)$

$A = Frontal\ area\ of\ vehicle\ (m^2)$

$n_{bw} = Battery\ to\ wheel\ efficiency$

$n_{brk} = Efficiency\ of\ brakes$

$C_d = Coefficient\ of\ drag$

$C_{rr} = Rolling\ resistance\ (of\ tires)$

$W_T = vehicle\ curb\ weight + 2\ passengers\ at\ 70kg$

$v_{rms} = Root\ mean\ squared\ of\ velocity\ \left(\frac{m}{s}\right)$

$v = Average\ velocity\ \left(\frac{m}{s}\right)$

$Z = Road\ grade\ \left(\frac{r}{100}\right)$

$t_f = \%\ time\ at\ road\ grade$

$a = Mean\ acceleration\ or\ deceleration\ of\ vehicle\ \left(\frac{m}{s^2}\right)$

$D = Driving\ range\ (m)$

$E_p = Battery\ pack\ energy\ (kWh)$

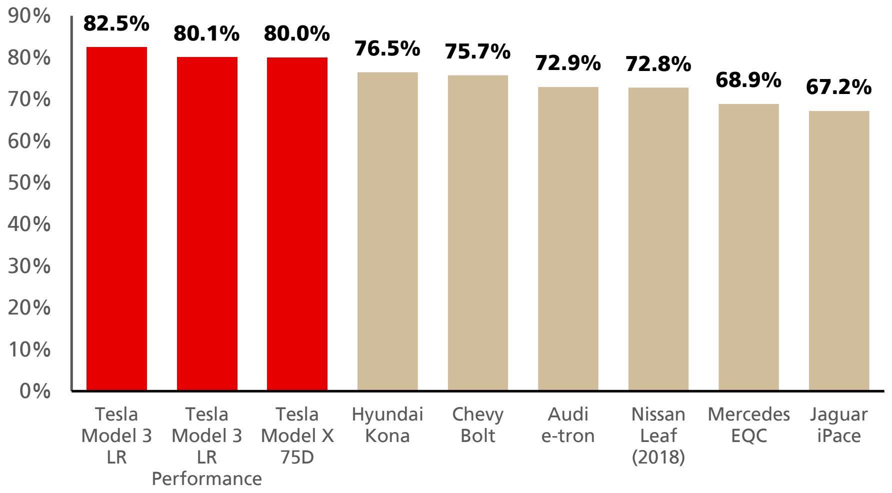
Source: UBS

In simple terms, this formula says that the energy required (in kWh) to drive a certain distance is a function of the aforementioned four factors, which themselves are driven by the shape of the car, its weight and the battery-to-wheel efficiency. We know, for example, that Tesla is doing very well in terms of the drag coefficient of only 0.23, which sets a new benchmark in its segment, including ICE cars. We also know that Tesla has the best battery capacity to weight ratio of any EV in the market, resulting in a weight advantage over peers. So how can we find out whether Tesla's battery-to-wheel efficiency is best in class? We compare the Model 3 to the Audi e-tron, the Mercedes EQC, the Hyundai Kona EV and Jaguar I-Pace as most recent incumbent launches. And as a reference, we also included the Tesla Model X, which has already been on the market for three years.

The Model 3 is indeed the model with the best battery-to-wheel efficiency in the market

Results show that the Model 3 is indeed the model with the best battery-to-wheel efficiency in the market. For example, what the Tesla Model 3 teardown revealed is that the inverter uses silicon carbide, which is known for its higher efficiency. We also found a particularly efficient e-motor design in the Model 3. While our formula does not reveal where exactly the Model 3's best-in-class efficiency comes from, the results show that this is an area of competitive advantage. Another observation is that the Audi e-tron, which has a sophisticated regenerative braking system compared to the Mercedes and the Jaguar, also achieves a better efficiency ratio than these peers.

Figure 29: UBS battery-to-wheel efficiency model underscores Tesla's lead

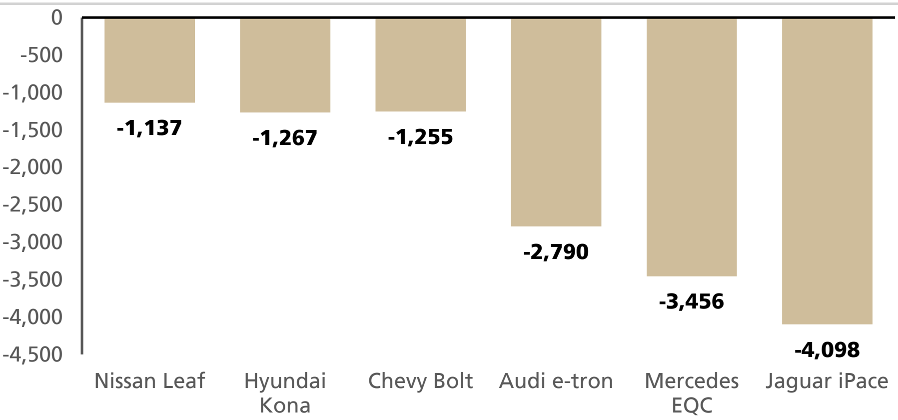


Source: UBS estimates

Tesla can employ a smaller battery than its competitors, which saves money, straight into the bottom line

But why does it matter? Most likely, no consumer will ever do these maths before making a purchasing decision. It matters because in order to achieve a certain range, Tesla can employ a smaller battery than its competitors, which saves money, straight into the bottom line. The larger the car (and the battery capacity), the bigger the cost difference. Taking the example of the Model 3, it achieves 82% efficiency instead of 67% for the Jaguar I-Pace. This translates into a "saved" battery capacity of ~21kWh. In other words, Jaguar had to put 21kWh more battery capacity in the I-Pace than if they had the same battery-to-wheel efficiency as the Model 3. In US dollar terms, the higher cost for Jaguar (P&L impact) from the lower efficiency is a very significant ~US$4k per vehicle sold. Just as a reminder, this is before taking into account the fact that Tesla also managed to design the car with a segment-leading drag coefficient and the lowest battery pack weight per kWh, which adds to the saved battery capacity.

Figure 30: Cost disadvantage of legacy OEMs vs Model 3 (US$ per vehicle)

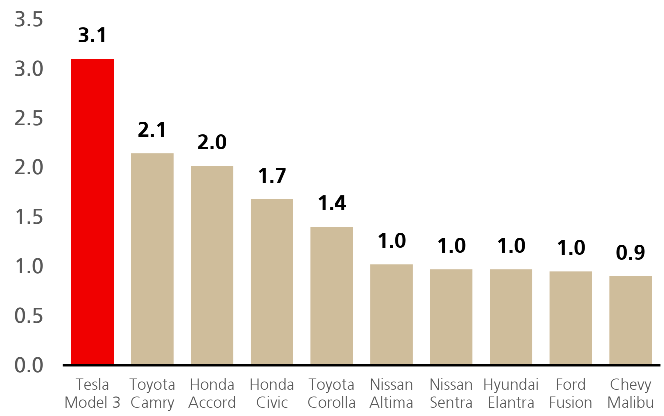


Source: UBS estimates

Premium incumbents start to feel the pain

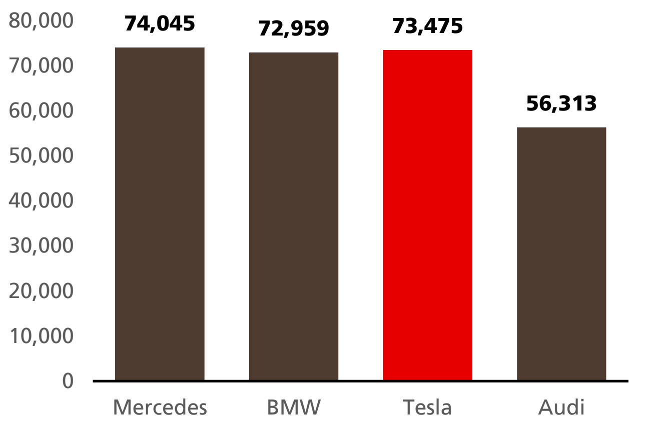
The Model 3 has become the best-selling sedan in the US market by value in Q3, and Tesla has outperformed Mercedes, BMW and Audi in monthly sales since September. The Model 3 is expected to arrive in Europe and Asia in Q1 19, and we expect the German premium brands to be most negatively affected.

Figure 31: Best-selling sedans in the US by revenue in Q3/18 (US$bn)



Source: Tesla

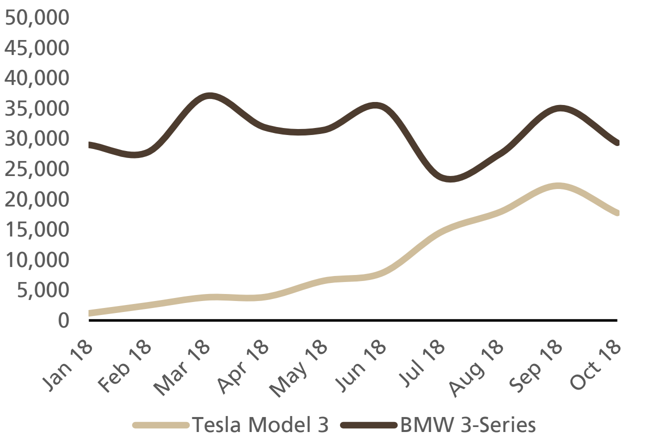
Figure 32: Tesla vs German OEMs' US unit sales, August-October 2018



Source: Company data, UBS

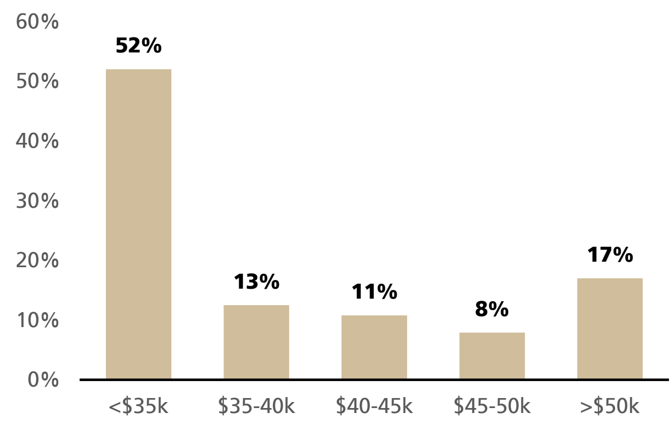
A UBS Evidence Lab consumer survey in Q4 17 showed that the BMW 3-series is widely seen as the closest competitor to the Model 3, which is why we see substantial risk to 3-Series sales in 2019. But also Mercedes' C-Class and the Audi A4 could be negatively affected. Trade-in data for the Model 3 shows that also owners of mass-market vehicles trade up, which might slightly soften the negative impact for those premium compact models.

Figure 33: Model 3 US sales vs BMW 3-series global sales



Source: Company data, Insideevs

Figure 34: Model 3 – trade-in vehicles by price segment



Source: Tesla

What next? The ultimate answer about Tesla's lead will come from two key 2019 launches

There are two upcoming EV models that will provide strong evidence as to how significant Tesla's lead is.

- **The Porsche Taycan** will be the global benchmark for incumbents in the performance EV segment, in our view. So far, Porsche only said that its acceleration 0-60mph will be below 3.5 seconds (which is already achieved by Tesla's Model 3 Performance version) and that it will be repeatable, for example, on a race track. We think the Taycan needs to match or beat Tesla in KPIs, such as power-to-weight ratio and acceleration, to underscore that legacy players can also build top-notch performance EVs. Already known is the fact that Porsche will use 800V on-board voltage, which doubles the charging

power to up to 350kWh (Tesla currently uses 120kW), and offer induction charging (not available for Tesla yet).

- **The Volkswagen I.D.** will be the first mass-market incumbent EV built from scratch on a dedicated electric platform (MEB), which is expected by VW to reach >1m units p.a. by 2025. Various auto journals reported that the first car, "I.D. Neo", will be available in three battery configurations, enabling a WLTP range of 330km, 450km and 550km, respectively. The base version is expected by VW to have a German retail price well below €30k (including VAT). We estimate that VW can sell ~200k units of this car in 2020 in Europe and China. If the new architecture does not meet Tesla's level of sophistication in terms of power electronics, weight per kWh, and manufacturing cost, it would put Tesla in pole position for mass-market EV penetration.

Figure 35: Volkswagen I.D. Neo (concept version)

Source: Volkswagen

Figure 36: Porsche Mission E (concept version of Porsche Taycan)

Source: Porsche

Can Tesla sustain its cost lead in China?

Tesla earlier this year announced to establish a 100%-owned subsidiary in China, as the first foreign OEM. It said it will build an assembly plant and another battery Gigafactory. We estimate local Tesla production could start in 2021/22. From the perspective of the Chinese consumer, this would lower Tesla's price for the Model 3 by 33%, as our analysis shows.

One key moving part is the local battery production. While there is little doubt that Tesla will replicate the Gigafactory model by partnering with a cell supplier, it is unclear whether that partner will be Panasonic. Panasonic has not shown any interest so far to be Tesla's partner in China. This raises questions as to whether Tesla will hold on to the NCA cell chemistry or eventually move to NMC. We think there is a reasonable chance Tesla sticks with NCA, because, as explained above:

(1) The technology should have a sustained cost advantage over NMC;

(2) Tesla's edge lies in the BMS it has created for NCA cells;

(3) The different form factor of NMC would likely require re-engineering of the entire battery pack.

On that basis, Tesla would be able to defend its cost lead or even increase it, because the other global brands so far have shown a less aggressive stance in terms of scaling up local EV production in China.

Potential significant price cut

Tesla enjoys some brand premium in China, partly due to its technology leadership

Partly due to this technology leadership, Tesla enjoys a brand premium in China. Despite the high price points of the existing Model S and Model X, it still managed to sell 17k units of these models in China in 2017, up from 11k in 2016. We estimate the overall market size of the Models S/X pricing points at merely 200k units a year in China; on that basis, Tesla has taken ~8% share of that segment. The Model 3 is not yet available in China, but we would expect a local factory to produce this model, given its potential high volume.

We believe cost savings from localisation come from a number of aspects: (1) savings on the tariff on cars; (2) savings on direct labour cost; (3) savings on capex depreciation cost due to cheaper capex requirements in China; (4) savings in the bill of materials due to local sourcing; and (5) savings on the high whole-vehicle shipping cost. But this might be partially offset by Chinese tariffs on imported parts, which currently stand at 6% only. Among these, we think the tariff savings and direct labour cost savings are the most visible, suggesting a >US$20k saving on a Model 3 short-range variant with ADAS option.

Tariff savings play a key role

Tariff savings are the most straightforward among the above list. Currently, a 40% tariff is applied on all US-made cars, plus 16% VAT. Even if the trade war ends, we expect the tariff would still remain at 15%, as per the current rate. We estimate that for a Model 3 short-range version with ADAS option priced at US$40k in the US, this tariff plus associated additional VAT could amount to Rmb136k (US$20k) in a 40% tariff scenario, and Rmb51k (US$7.4k) in a 15% tariff scenario.

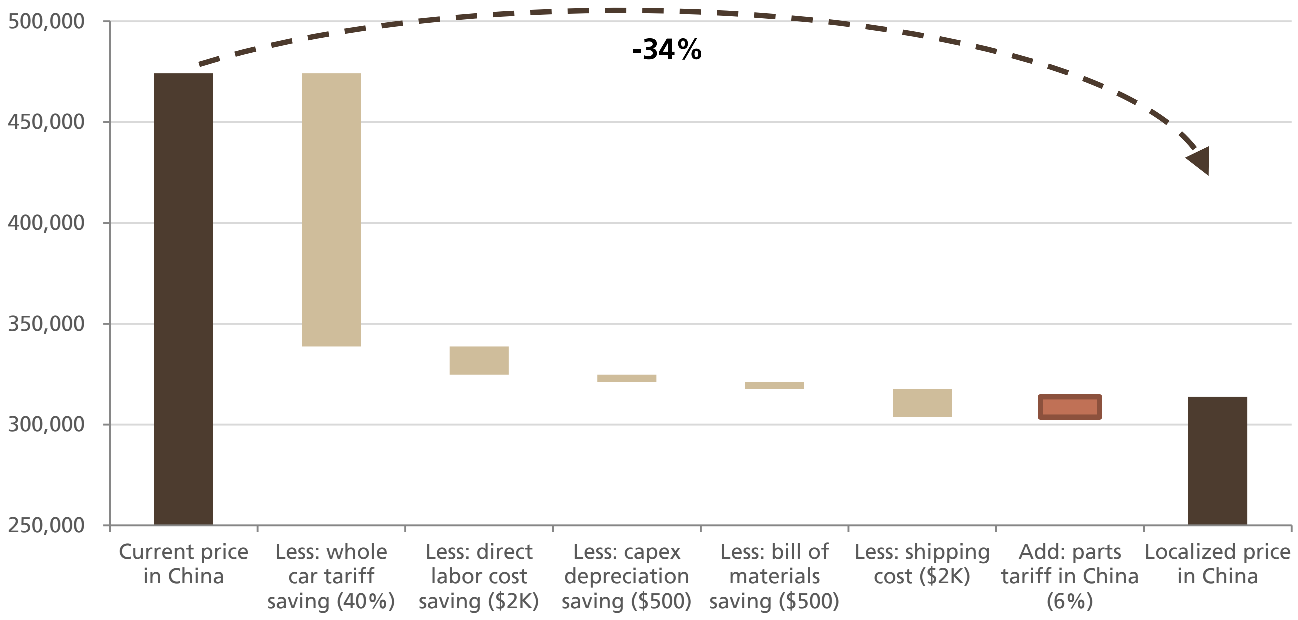
Substantial labour cost savings

Savings on labour costs are also substantial. We estimate that, assuming an annual production of 300k Model 3 units at the Fremont factory in 2020, the direct labour cost allocated to each unit would amount to US$2.5k. While the average payroll for assembly workers in California is over US$100k, it would be merely US$20k in China. Assuming the same productivity per worker in both countries (and Chinese workers might offer even more flexibility on working hours during peak/slack seasons), we estimate direct labour cost saving per unit would be Rmb14k or US$2k once the Chinese factory ramps up production.

There are potentially some savings in depreciation and bill of materials as well, which are less transparent. We assume US$510 per car depreciation charge saving due to lower capex spending in China, and US$1,480 per car for the bill of materials due to local sourcing. Shipping cost to China, which amounts to US$3k (Rmb20k) for the whole vehicle currently, could be reduced by about 70% if just components are shipped. This comes at the cost of additional tariff on parts, which is levied at 6% today.

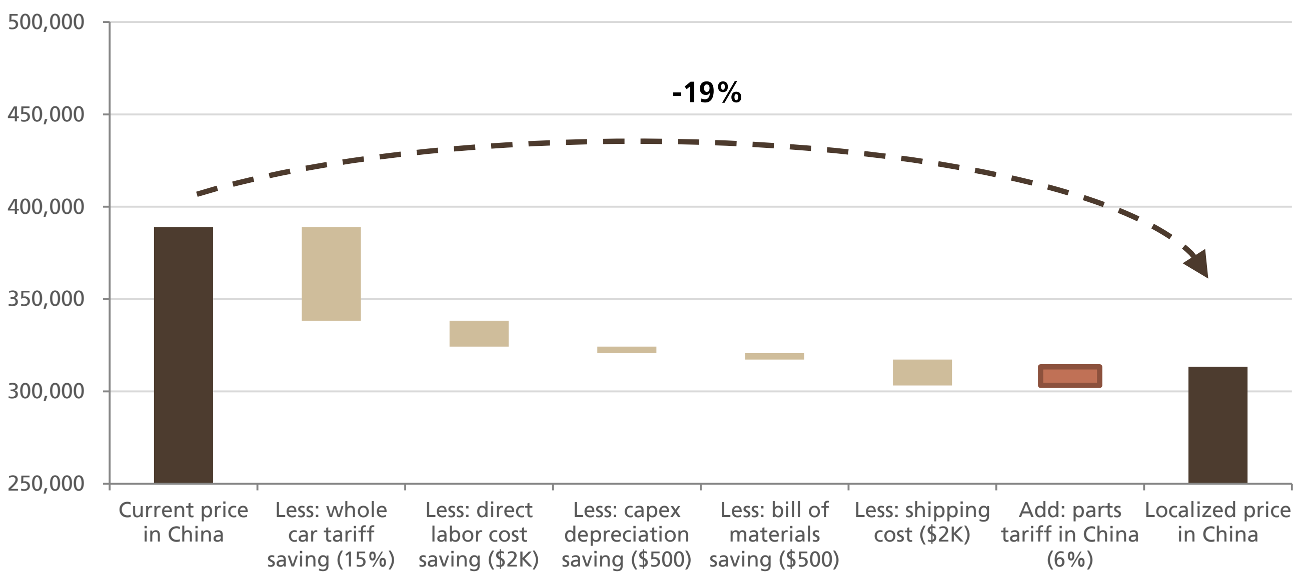
Based on our above calculations, we estimate the short-range version Model 3 with ADAS option, priced at US$40k in the US, could be sold at Rmb314k only, after localisation, compared with Rmb474k in a 40% tariff or Rmb389k in a 15% tariff scenario.

Figure 37: UBS estimates of Tesla Model 3 price in China if production is localised, assuming 40% tariff included in the current price as starting point (Rmb)



Source: Company data, UBS estimates

Figure 38: UBS estimates of Tesla Model 3 price in China if production is localised, assuming 15% tariff included in the current price as starting point (Rmb)



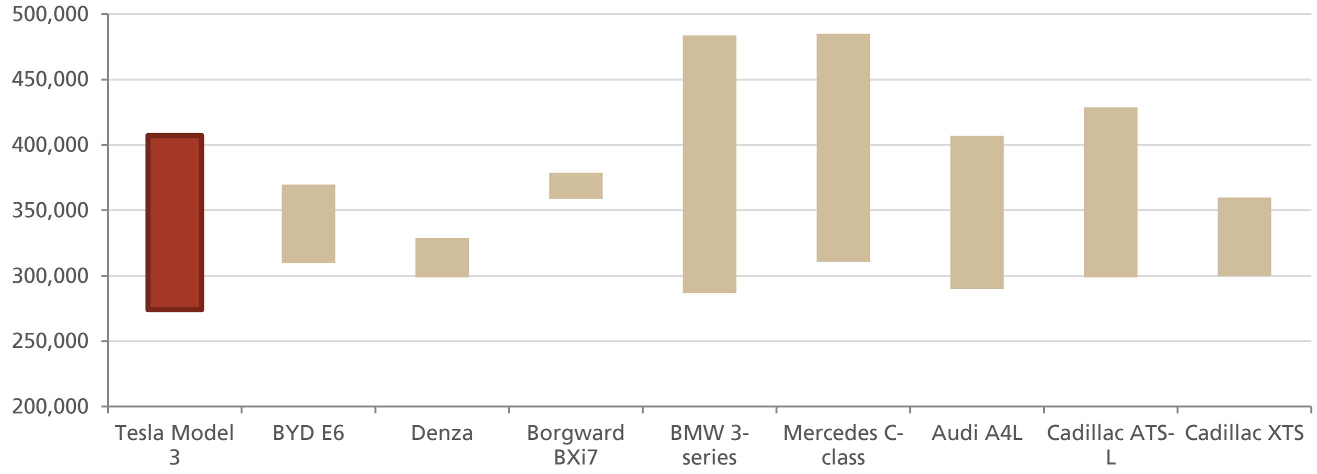
Source: Company data, UBS estimates

Key losers among the competition

We believe that Model 3 localisation could change the competitive landscape in China's premium car market. Potential relative losers could be the BYD E6, Denza or Borgward BXi7, but it might also impact global premium cars such as the BMW 3 series, Mercedes C-class and Audi A4L, given the price overlap.

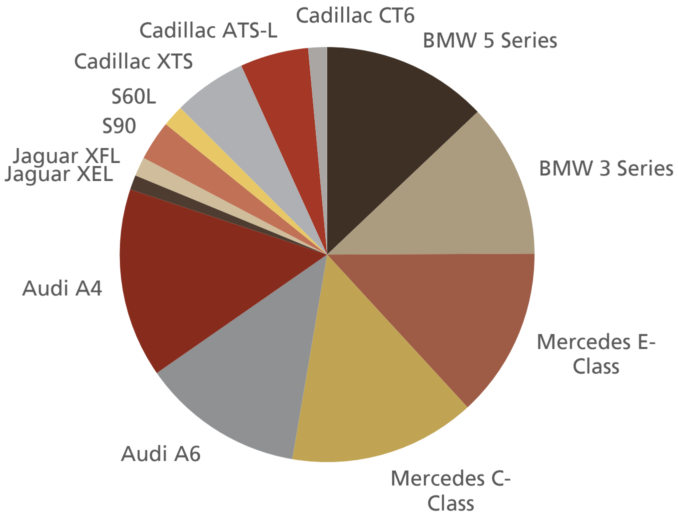
Model 3 localisation would likely change the competitive landscape in China's premium car market

Figure 39: MSRP* of selected EV models in China (Rmb)



Source: Company data, UBS
* Manufacturer's suggested retail price.

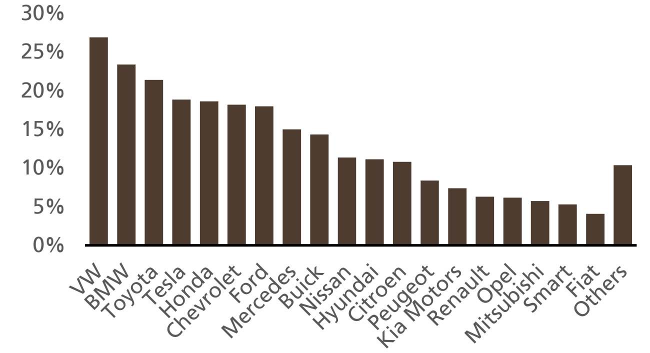
Figure 40: China – locally produced premium sedan market shares



Source: Company information, UBS

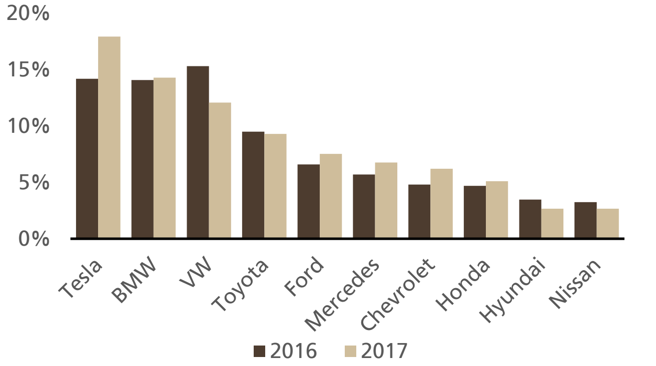
A UBS Evidence Lab survey on customers' willingness to buy an EV suggests that the Model 3 has the highest customer overlap versus the BMW 3-series. In China, this would unavoidably impact BMW Brilliance's business, in our view.

Figure 41: Brands considered prior to intending to purchase Model 3 – China



Source: UBS Evidence Lab

Figure 42: Top choice of BEV by brand – China



Source: UBS Evidence Lab

Chinese OEMs: Opening up is the trend

The Chinese EV battery market has consolidated in recent years, with CATL the national champion

During the past few years, the Chinese EV battery market has consolidated, with CATL being the undisputed national champion. The rest of the battery makers are dwarfed by CATL, and some high-volume ones fell into liquidity trouble after subsidy cuts, such as Shaanxi J&R. Korean and Japanese competitors are effectively blocked out of the market, partly due to OEMs fearing to become unable to receive subsidies if they employ foreign batteries, even though some OEMs, such as SAIC, GAC and GWM, originally fitted their cars with LG Chem batteries.

The CATL-dominated Chinese battery market looks too concentrated to us

Such a high market share and almost monopoly of CATL in the high-end EV market could entail some negative effects. In our view, cost deflation and quality improvements could be even faster than today if foreign battery makers were allowed to compete in this market, and government subsidies could be saved, while the EV market share could be even higher than today. If foreign battery makers could help Chinese OEMs build better EV products, these products could be more competitive on the global market. Contrasting with the highly competitive and further fragmenting EV market, the CATL-dominated Chinese battery market looks too concentrated to us.

Opening up the EV supply chain could help Chinese OEMs build better cars and improve their export potential

The teardown project suggests that LG Chem enjoys some technological and cost advantages over CATL, with its pouch shape, higher nickel content and lower electrolyte usage. We found this a bit surprising, given that CATL enjoys lower labour costs and higher volume scale than LG Chem. If LG Chem's cost advantage is maintained beyond 2020, and government subsidies effectively drop to zero, we think at least some foreign OEMs would likely start to employ LG Chem batteries in their respective China JVs, which might be even easier for them, given that they might also use LG Chem batteries in their European factories. Chinese brands, in order not to lose out in the competition, might also shift some orders to LG Chem. Opening up the EV supply chain would help Chinese OEMs build better cars, in our view, also lightening up their export possibilities.

For vertically integrated OEMs, owning a battery business could change from edge to disadvantage

Opening up the battery market could weaken the position of some vertically integrated OEMs. Owning a battery business might gradually change from being an edge to being a disadvantage if the battery quality and cost fail to catch up to leading standards.

Is there one winning cell format?

Tim Bush
Asia Oil Refining and Chemicals

Taewoo Lee
APAC Tech

Kanji Yasui
Japan Conglomerates (Industrials and Consumers)

Paul Gong
China Autos

Evidence from the teardown demonstrates that Tesla's round cell produced by Panasonic leads in terms of technology, materials and costs. However, the cell has safety and packing complexity disadvantages. Cylindrical cells are smaller in size and weight compared with other formats. Consequently, a much greater number of cells is required for a battery pack. For example, Tesla's Model 3 requires 4,416 Panasonic cells for a 77 kWh battery pack whereas Chevy Bolt's 63 kWh battery pack requires 288 LG Chem pouch-format cells. More cells result in greater assembly costs (connecting all the cells together), increased safety risk, and require a more sophisticated battery management system (BMS). Our BMS research shows that Tesla's in-house BMS is a critical factor in overcoming the safety risks associated with greater cell numbers. The BMS could be the barrier to entry for other OEMs looking to adopt the cylindrical format.

LG Chem's pouch format shows advantages in terms of technology, materials and costs. In some areas, such as gravimetric energy density (Wh/kg), the pouch format is superior to Panasonic's cylindrical cells. However, the cells' complex winding and folding process results in high manufacturing costs. Additionally, absence of a rigid housing as compared to the prismatic format makes it relatively less safe. In our optimised production scenario, the difference in cell cost per kWh between Panasonic and LG Chem is only ~10% versus ~20% today. If LG Chem successfully shifts to an 811 cathode, the price difference could drop further.

Prismatic cells are higher cost due to a greater number of components, a more complicated manufacturing process, sub-optimal space utilisation and excess material usage. However, their rigid metal cell housing and high number of safety features make prismatic the safest format.

Figure 43: Overview of battery cell comparison

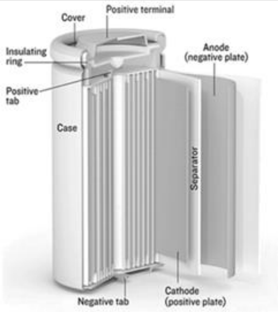
Battery found in...	BMW i3	Chevy Bolt	Tesla Model 3	Geely Emgrand EV
Supplier	**Samsung SDI**	**LG Chem**	**Panasonic**	**CATL**
Ah	94	60	4.8	70
Voltage	3.65	3.65	3.65	3.65
Wh	343.1	219	17.52	255.5
Weight (g)	2,026.4	835.4	68.5	1,250
Number of cells	96	288	4,416	--
Total kWh	33	63	77	--
Area				
Cathode (cm^2)	34,433	14,372	1,005	24,099
Anode (cm^2)	38,632	15,284	1,089	25,810
Separator (cm^2)	45,223	15,599	1,136	29,159
Electrolyte (ml)	179	96	5.3	170
Area/kWh				
Cathode (cm^2)	100.36	65.63	57.36	94.32
Anode (cm^2)	112.60	69.79	62.16	101.02
Separator (cm^2)	131.81	71.23	64.84	114.13
Electrolyte (ml)	0.52	0.44	0.30	0.67
Material				
Cathode	NMC 111	NMC 622	NCA	HiNi
Anode	Graphite	Graphite	Graphite	Graphite
Separator	PP.PE.PP 3-layer shutdown	PE	PE	PE
Electrolyte	LiPF6	LiPF6	LiPF6	LiPF6

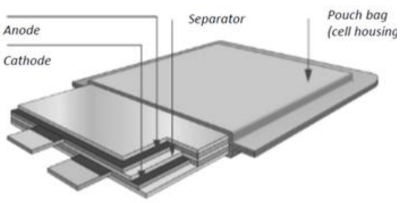
Source: UBS Evidence Lab

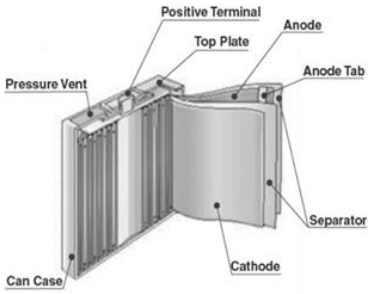
What are the key differences among the battery cell makers and three cell formats?

In partnering with P3, UBS Evidence Lab tore down and compared the battery cells from each of the battery suppliers – BMW i3 (94Ah) cells made by Samsung SDI, GM Bolt cells made by LG Chem, Tesla Model 3 cells made by Panasonic, and the latest CATL battery cells used by several Chinese BEV models. Additionally, P3 provided a 'first-take' cost estimate for Samsung SDI's new 120Ah cell type that will be used in the BMW i3 going forward. Figure 44 provides an overview of the key pros and cons.

Figure 44: Key summary of pros and cons by cell format







	NCA/cylindrical type	NMC/pouch type	NMC/prismatic type
Manufacturer	Panasonic	LG Chem, SK Innovation	Samsung SDI, CATL
Pros	High energy density	Large cell size	Large cell size
	Lower cell cost	More stable chemistry	More stable chemistry
	Lower pack cost	More room for energy density improvement	More room for energy density improvement
	Mature technology – optimised	More room for cell size expansion	More room for cell size expansion
		More flexible form factor	Better safety features; more safety components
Cons	Less stable chemistry	Cell cost more expensive vs NCA	Cell cost more expensive vs NCA
	Small cell size = higher number of cells needed	Lower energy density vs NCA	Lower energy density vs NCA
	Requires advanced BMS with precise control	Lower level of automation	Limited form factor due to fixed can size
	Limited room for energy density improvement	High manufacturing costs	More number of components
	Limited room for size expansion	Less safety feature vs prismatic	More complex manufacturing process

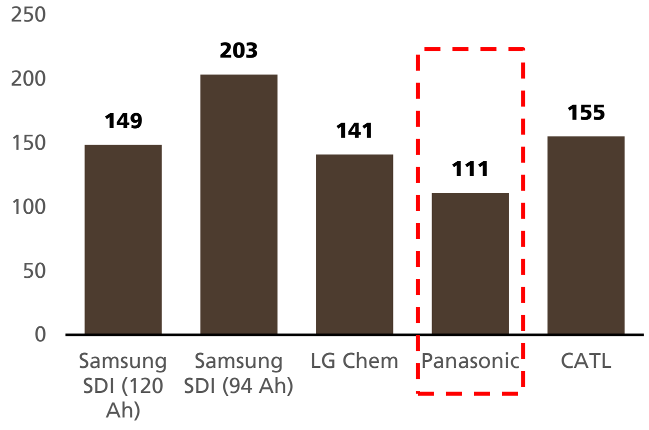
Source: UBS Evidence Lab

NCA cylindrical battery cell key features

NCA cylindrical provides the highest energy density solution at the lowest cost

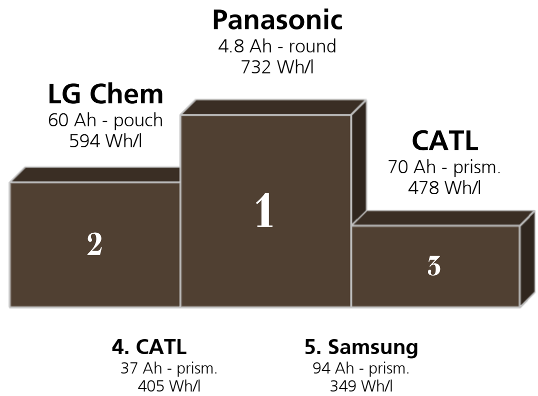
NCA chemistry in cylindrical cells is the battery cell type adopted by Tesla, with the battery cells supplied by Panasonic. The teardown result shows that the NCA cylindrical battery has a clear lead in technology, chemistry and costs. NCA currently has the highest nickel content in cathode and therefore the highest energy density, leading to many of the key advantages NCA has, including having the lowest cell and pack cost per kWh. It is also the most mature technology among the three, hence the production process is almost fully optimised. However, the cell chemistry is less stable by nature, and therefore has to be canned in a cylindrical format with limitation in cell size. This leads to the NCA/cylindrical battery's main disadvantage being the safety aspect. As the cell size is limited with not much room to increase, the battery pack needs to incorporate a greater number of cells (4,416 cells in Tesla Model 3 battery pack) and requiring advanced BMS that has precise control over the individual cells.

Figure 45: Cell cost comparison (US$/kWh)



Source: UBS estimates

Figure 46: Energy density comparison (Wh/l)



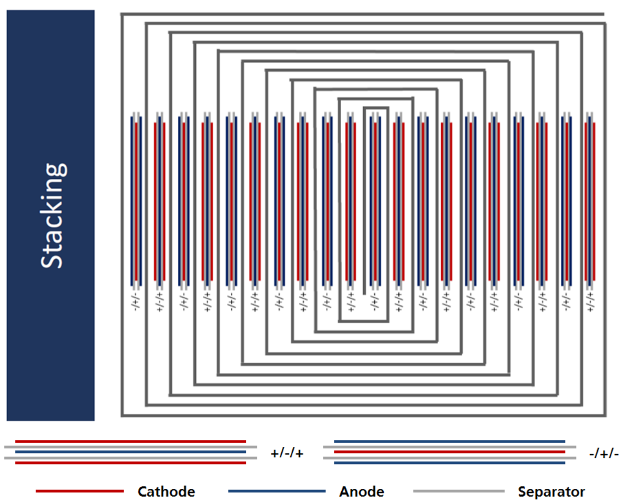
Source: UBS

NMC pouch battery cell – key features

NMC pouch type provides larger and more stable cells with more flexible form factor

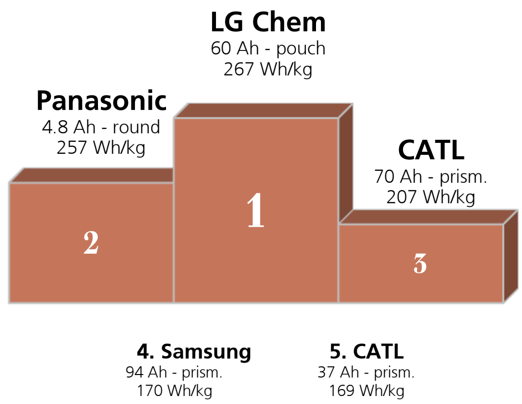
NMC chemistry in pouch type format is the battery cell type currently adopted by the GM Bolt, as well as by many other models. The main battery cell supplier for this type is LG Chem, with SK Innovation also producing the same format. One of the key advantages of the NMC pouch type is the relatively more stable cell chemistry. This allows the individual cell size to be far bigger compared with NCA cylindrical, so the battery pack can contain a smaller number of cells (288 cells in GM Bolt battery pack). The chemistry leaves further room to improve in terms of energy density and cell size. The pouch type is essentially battery materials contained in aluminium foil, therefore the format allows for more flexibility in form factor when OEMs design the space for the battery pack. However, the energy density is lower and the overall cell cost higher compared with NCA cylindrical. Also, the aluminium pouch format provides less safety features compared with prismatic cells.

Figure 47: LG Chem pouch cell stack and folding structure



Source: P3, UBS Evidence Lab

Figure 48: Gravimetric energy comparison (Wh/kg)



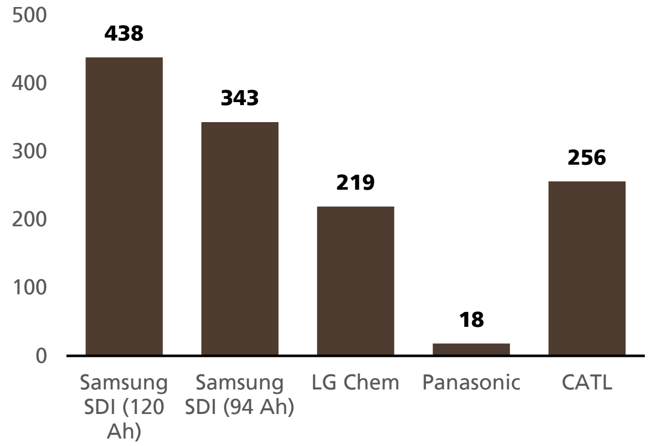
Source: UBS

NMC prismatic battery cell – key features

NMC chemistry in prismatic type format is the battery cell type produced by Samsung SDI as well as CATL. NMC prismatic cells provide similar key advantages as described above for pouch cells: more stable cell chemistry and therefore larger battery cell size. The prismatic can-type packaging also allows more safety features to be embedded at the cell level, including overcharge safety device, degassing vent, and nail safety device, as demonstrated in the Samsung SDI cell teardown. However, these additional components lead to a more complex manufacturing process. Also, the fixed dimension of the cell suggests sub-optimal use of cell space. The prismatic type also shares the pouch type's disadvantage in that the energy density is lower and the overall cell cost higher compared with NCA cylindrical.

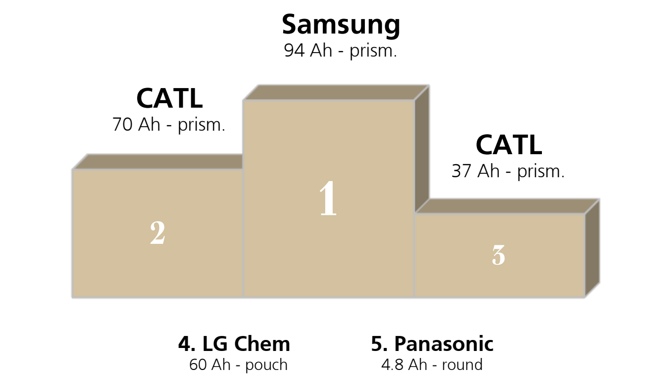
NMC prismatic type provides larger and more stable cells with more safety features embedded

Figure 49: Battery cell size comparison (Wh/cell)



Source: P3, UBS Evidence Lab

Figure 50: Safety feature comparison



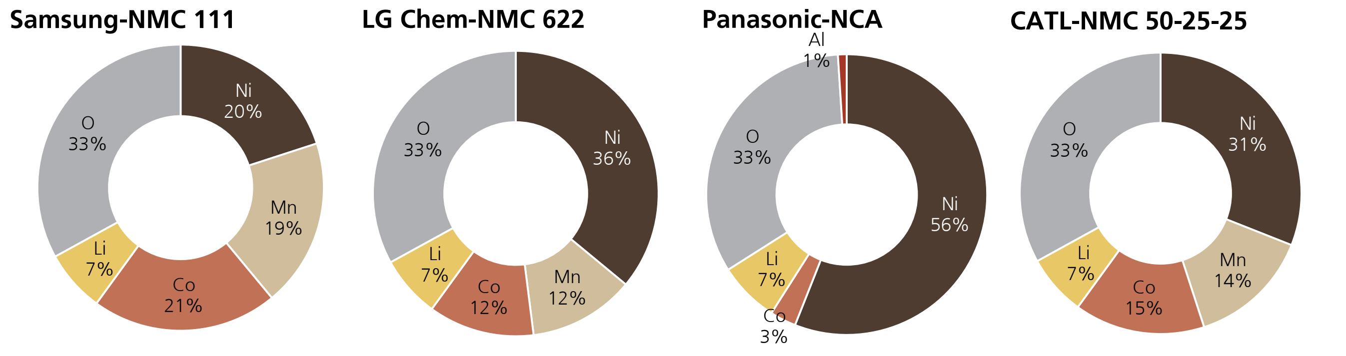
Source: UBS

How does the overall battery cell price compare?

Cell chemistry being the key determinant for cell price

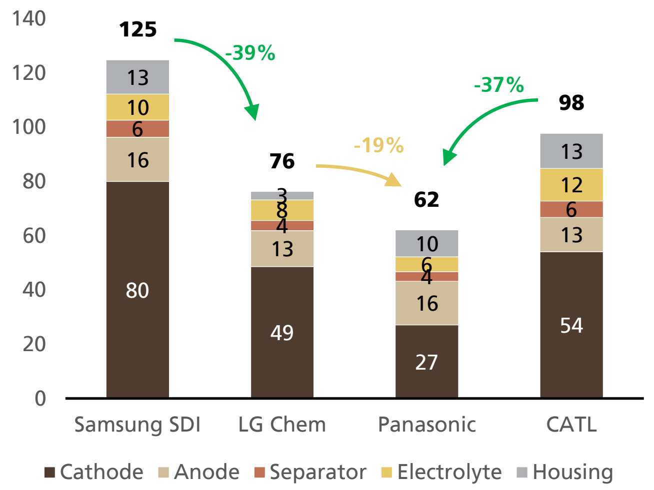
Our analysis concludes that the cell chemistry, ie, the raw material composition, is the key determinant in battery cell cost. Tesla Model 3 battery cells produced by Panasonic have the lowest all-in cost at US$111/kWh, supported by the NCA cell chemistry with the highest nickel content and lowest for cobalt. GM's Bolt battery cells made by LG Chem come second in cost at US$141/kWh, with the cell chemistry being NMC 622 in pouch format. This is rather closely followed by Samsung SDI's newly launched 120Ah cells for the new BMW i3 (UBS estimate) and CATL 70Ah cells for Chinese BEVs, which are NMC 622 and NMC 532, respectively, both in prismatic format. Samsung SDI's 94Ah cells trail in cost at US$203/kWh, mainly due to the material cost from using NMC 111 chemistry. The comparison shows the main differences in cost to be driven by the material cost, and battery cells with similar nickel content show a minimal price difference overall.

Figure 51: Cathode raw material share in comparison, by cell type



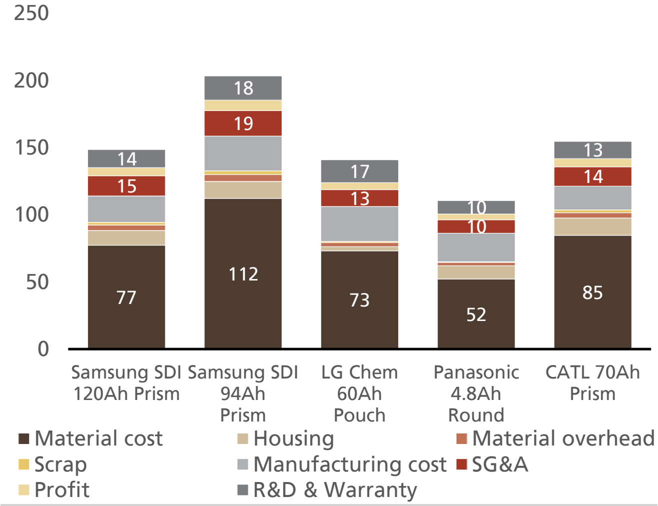
Source: UBS Evidence Lab

Figure 52: NCA is unbeatable in direct material costs (US$/kWh)



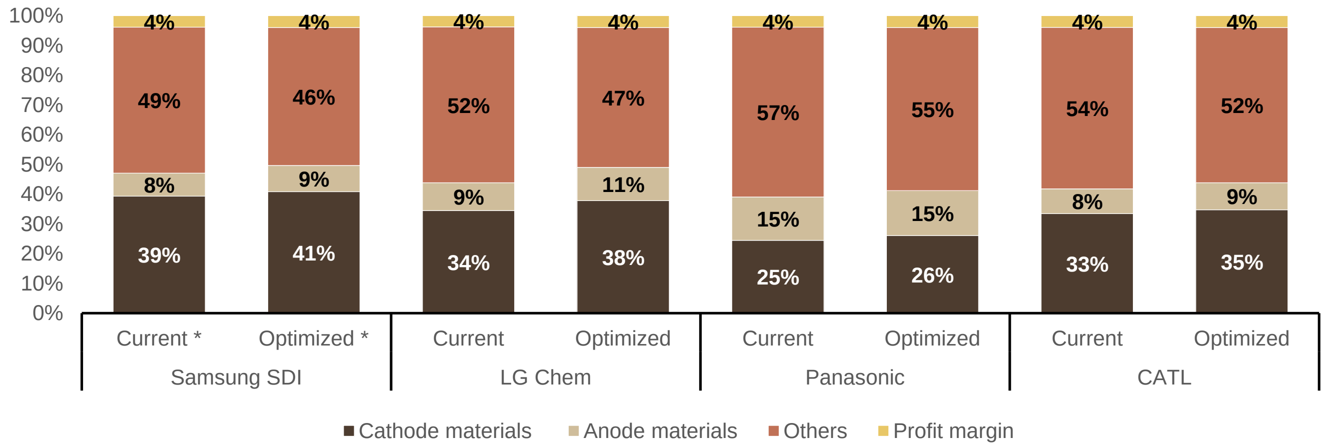
Source: UBS Evidence Lab

Figure 53: Current cell price estimate and comparison (US$/kWh)



Source: UBS Evidence Lab, UBS estimates

Figure 54: Cost breakdown by cell type



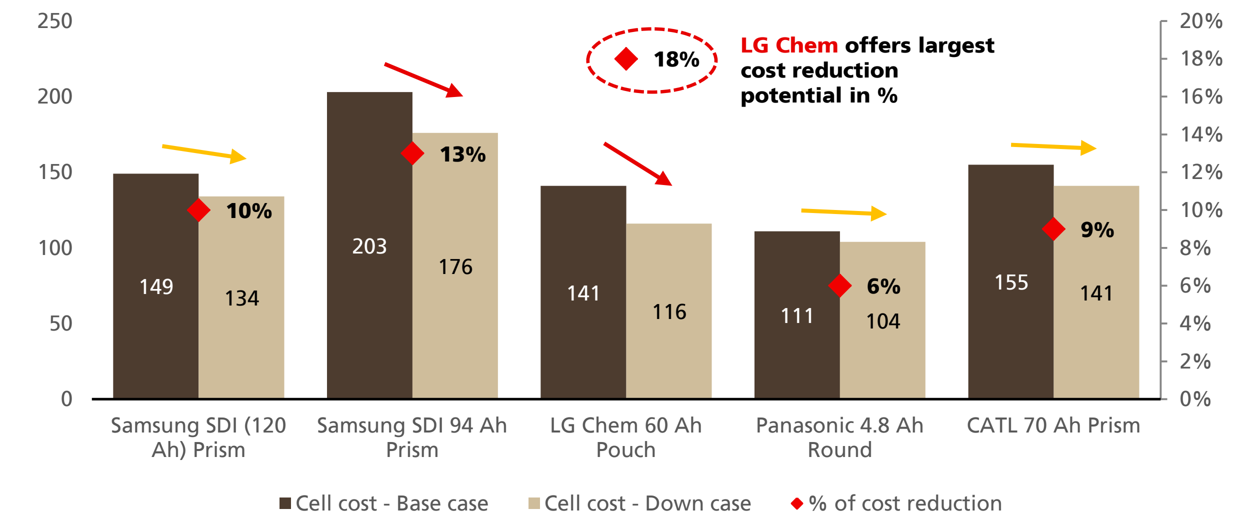
Source: UBS Evidence Lab * Current and optimized refers to production setup

Current cell chemistry could reach close to US$100/kWh with scaling

Our simulation of a cost-down scenario suggests that the battery cell makers could reach close to US$100/kWh in cell cost with the existing cell chemistry, just by increasing scale and making the manufacturing process more efficient.

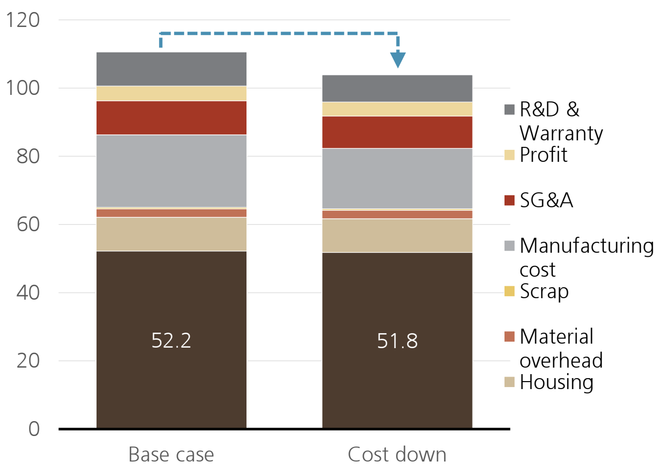
The key assumptions being made in the cost-down scenario include: improved capacity and line utilisation rate, increased equipment efficiency leading to higher throughput, lower active material purchasing prices given larger scale, and a lower percentage of R&D/sales.

Figure 55: Battery cell price base case versus optimized scenario (US$/kWh)



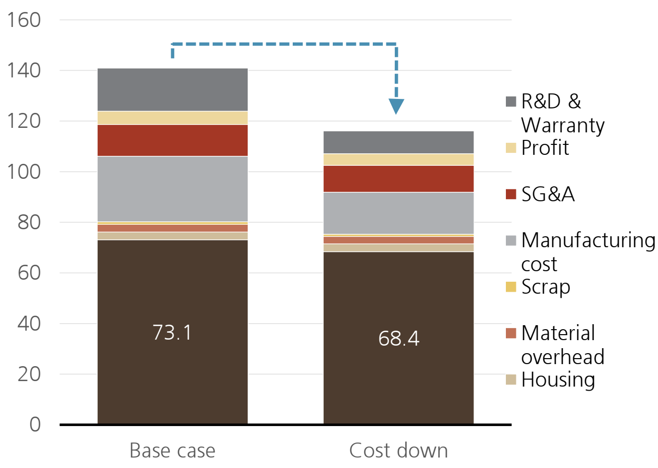
Source: P3, UBS Evidence Lab

Figure 56: Panasonic battery cell today vs. optimized production setup (US$/kWh)



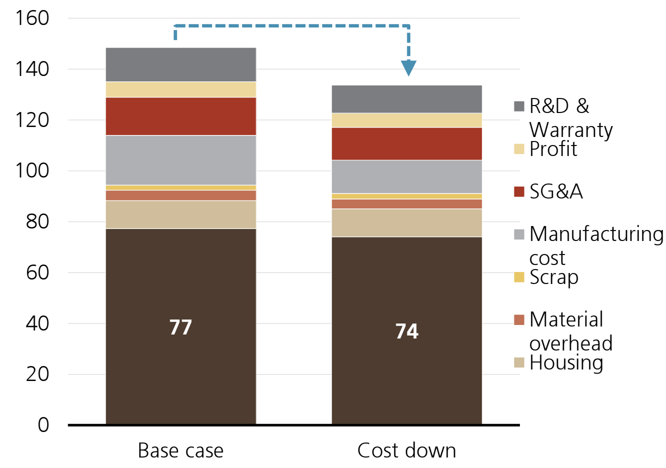
Source: P3, UBS Evidence Lab

Figure 57: LG Chem battery cell today vs. optimized production setup (US$/kWh)



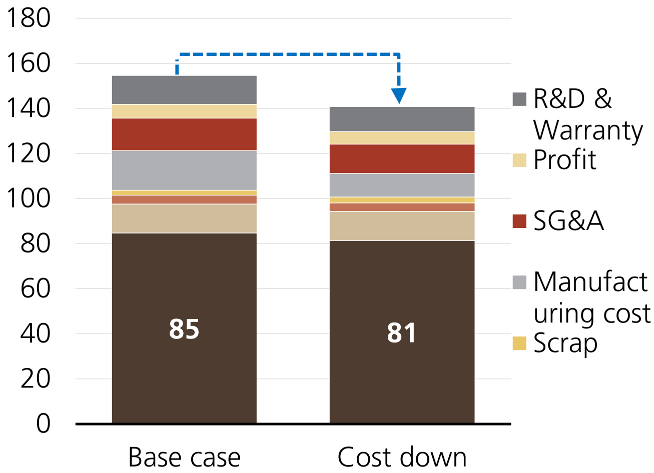
Source: P3, UBS Evidence Lab

Figure 58: Samsung SDI 120Ah battery cell today vs. optimized production setup (US$/kWh)



Source: P3, UBS Evidence Lab

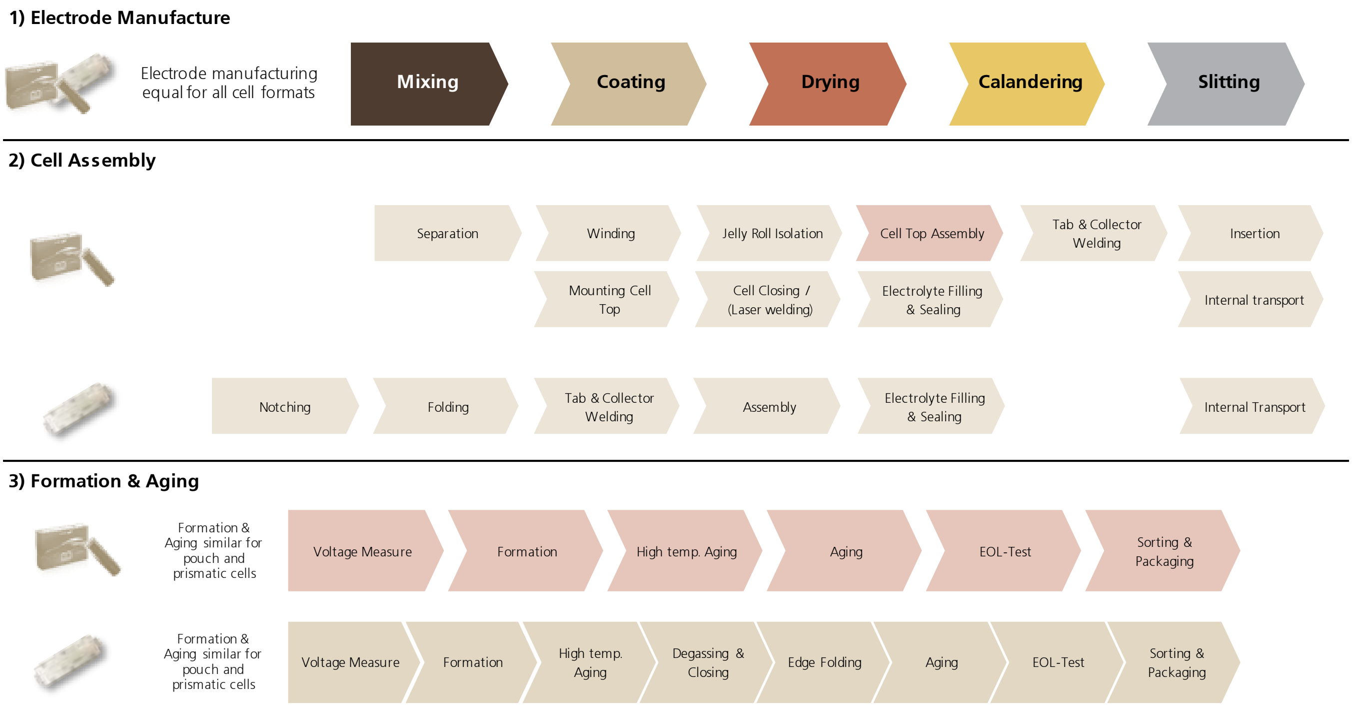
Figure 59: CATL battery cell today vs. optimized production setup (US$/kWh)



Source: P3, UBS Evidence Lab

How do manufacturing process and costs differ?

Figure 60: Cell manufacturing process



Source: P3, UBS Evidence Lab

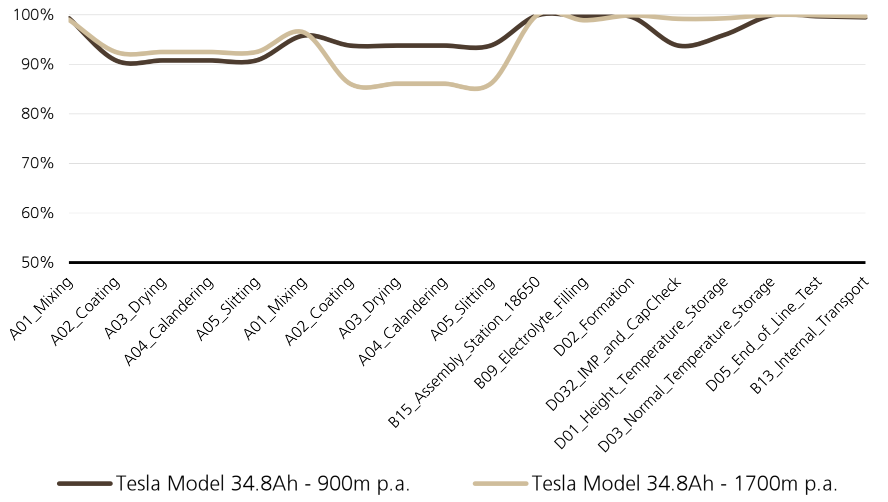
Manufacturing complexity and number of parts

Manufacturing complexity: cylindrical < pouch < prismatic

Cylindrical cells require the simplest manufacturing process among the three types, and only eight components. Prismatic cells entail the most complex manufacturing process with up to 30 components. The large number of components necessitates a large number of sub-suppliers. The manufacturing simplicity of the cylindrical format is reflected in the utilisation rate per production step. Utilisation for any given step never falls below 80%, whereas all other processes fall to 60% or lower

at individual steps, thus creating production bottlenecks. Pouch cells show a higher degree of manufacturing complexity but fewer components compared with the prismatic format.

Figure 16: Utilisation rate for Tesla's cylindrical cell



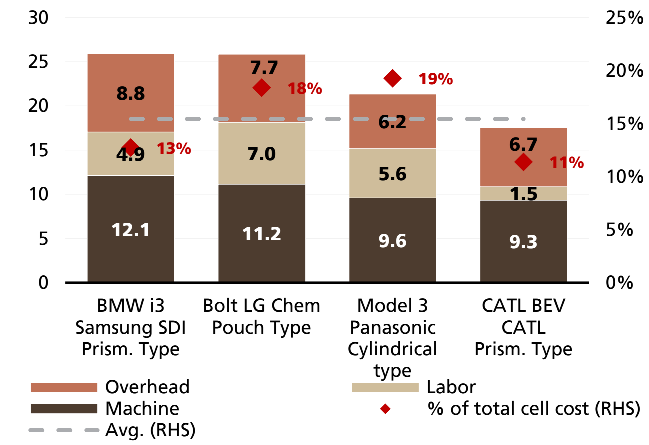
Source: UBS Evidence Lab

Who has the lowest manufacturing costs?

CATL enjoys the lowest manufacturing costs, due to China's low labour costs

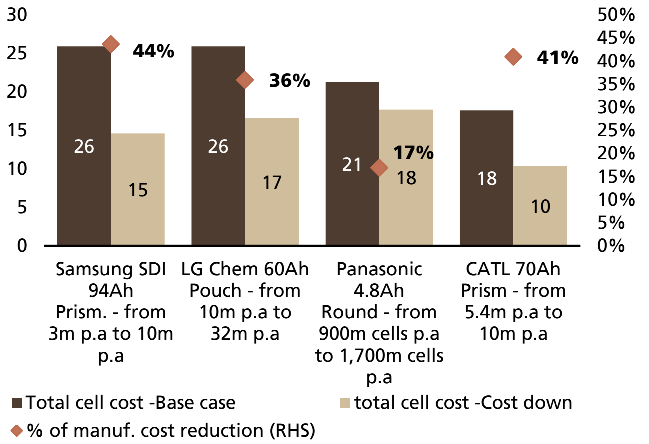
CATL's prismatic cells show the lowest manufacturing costs, despite the aforementioned manufacturing complexity disadvantages. This is largely due to hourly labour costs in China being significantly lower than in other manufacturing locations. Consequently, labour only accounts for 8.7% of CATL's manufacturing costs, or US$1.5/kWh. Excluding labour (manufacturing and overhead), NCA technology shows the lowest production costs.

Figure 61: Total manufacturing cost (ex raw materials) in USD/kWh



Source: P3, UBS Evidence Lab

Figure 62: Manufacturing cost – today vs. optimized (USD/kWh)



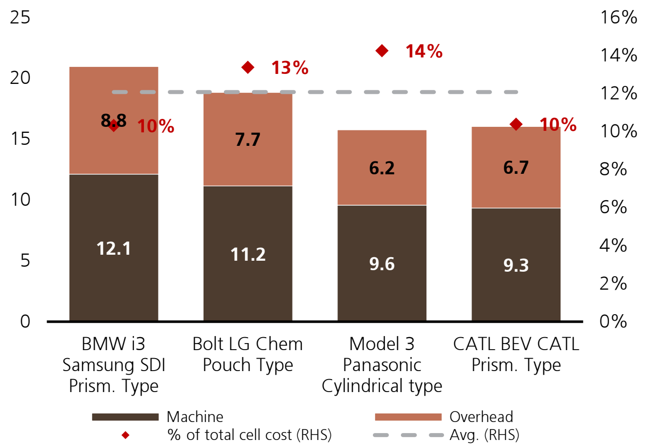
Source: P3, UBS Evidence Lab

Figure 63: Labour cost comparison by country

Company	Unit	Samsung SDI	CATL	LG Chem Panasonic	Samsung SDI	LG Chem
Location parameters		Hungary	China	US	South Korea	Poland
Labour costs						
Skilled worker	US$/h	7.87	6.47	34.86	20.63	8.00
Semi-skilled worker	US$/h	7.19	4.72	24.8	15.08	7.37
Non-skilled worker	US$/h	6.27	3.17	17.93	13.64	6.46
Exchange rate	Currency/US$	279 HUF/US$	6.82 CNY/US$	1.0 US$/US$	1,113 KRW/US$	3.68 PLN/US$

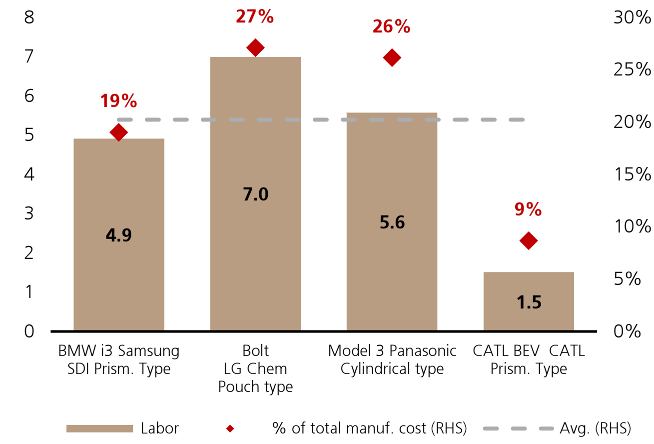
Source: P3, UBS Evidence Lab

Figure 64: Ex-labour manufacturing costs (USD/kWh)



Source: P3, UBS Evidence Lab

Figure 65: Labour costs (USD/kWh)

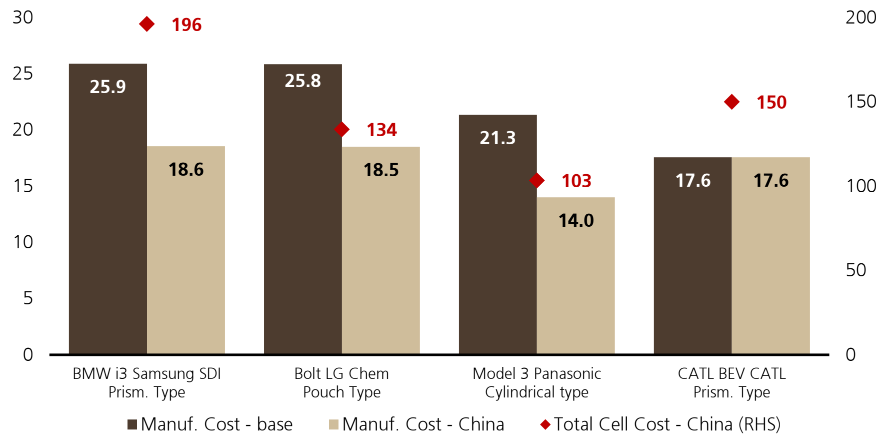


Source: P3, UBS Evidence Lab

What would manufacturing costs look like in China?

On an apples-for-apples comparison, we estimate the following cost structure would apply if all cell types were produced in China (Figure 66). On average, we expect cUS$7/kWh of cost savings for all three cell formats, ie, moving production to China would not put one cell type at a (dis)advantage to another.

Figure 66: Impact of production location on manufacturing and cell costs (USD/kWh)



Source: P3, UBS Evidence Lab

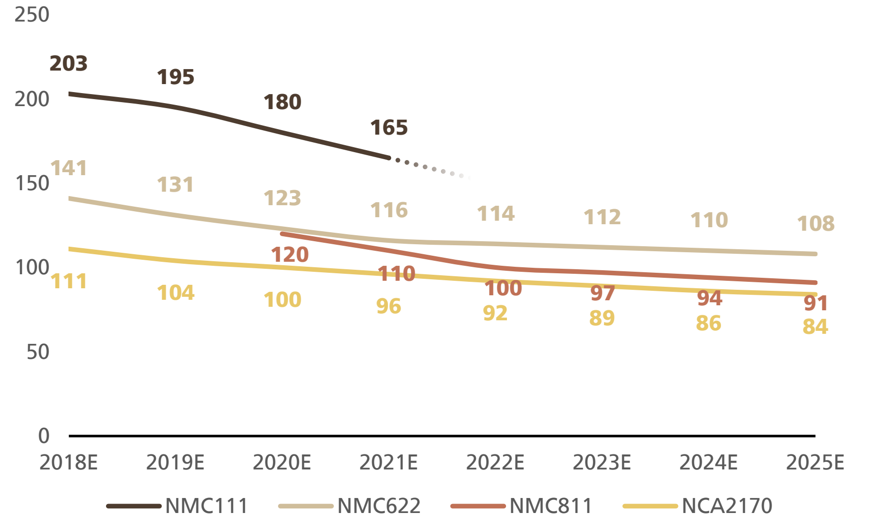
Can technology and scale result in cell cost falling faster than the market expects?

For the battery cells UBS Evidence Lab tore down, we estimate scale and optimized production to result in a **6-18%** cost decrease over the next two to three years, with further reduction potential from the shift to NMC811 after 2020. We believe that the **$100/kWh** cost target of leading cell makers is achievable in the early 2020s.

- In our opinion, **cost reductions from scale** slow down once production levels reach two or three times current levels. Once optimized utilization has been achieved, fixed costs will represent only 10-15% of total cell costs. Material costs such as cathodes, anodes, electrolyte and separators account for 56-66% of total cell costs.
- Further expected cost reductions come mainly from **material selection** (less cobalt, such as NMC811 or NCA). LG Chemical, Samsung SDI and CATL target upgrading to NMC 811 chemistry by 2020/21. With the shift in chemistry we expect battery cell costs to fall another 11-24%. Panasonic is already using upgraded nickel rich cobalt chemistry (NCA).
- We also expect foreign battery makers to **scale up China production** over the coming years and we believe this will result in another USD7/kWh reduction in cost. This is mainly due to much lower China labour costs.
- Finally we believe that **R&D** as a percent of sales can fall from 8-10% today to below 5% in the coming years. Most companies expect absolute R&D spend to remain at current levels as revenue grows in the coming years.

With these changes we expect most leading battery makers will reach US$100/kWh by 2021/22. With existing cobalt light technology and optimized production Panasonic could reach US$104/kWh already in the very near term.

Figure 67: UBS battery *cell* cost model, by chemistry ($/kWh)



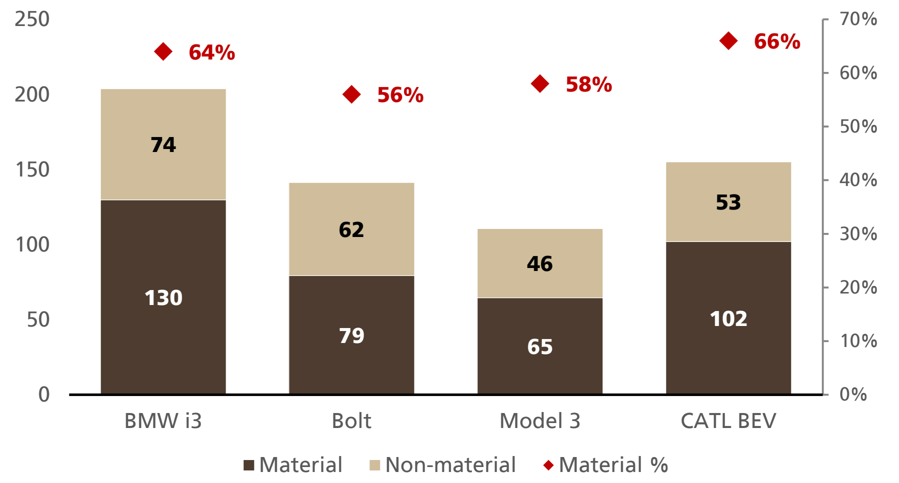
Source: UBS estimates

Scale merits to wear off after a certain volume level

The impact of economies of scale will likely diminish with production volume

The impact of economies of scale will likely diminish as production volume grows, as fixed costs only account for 10-15% of total cell costs. This represents a perhaps surprising departure from general manufacturing industry, where the marginal profit margin (the same as fixed costs, in theory) is usually 20-40%. In the near term, cost reduction will likely come from multiple factors such as material changes, optimized utilization rates and lower labour costs, as most suppliers plan to expand capacity two- or threefold. However, once suppliers reach a level of production at which almost all equipment is fully utilized, further cost reductions need to be derived from improved design concepts and material selection (NMC611 or NCA with less cobalt). The reason for the limited impact of economies of scale is the relatively high proportion of variable costs: the four major materials (cathode, anode, separator and electrolyte) account for 56-66%. These material costs are variable, directly linked to market prices and volumes, leaving little in the way of negotiating power. The remaining 30-36% of costs relate to equipment, labour, manufacturing overheads, scarp, SG&A, supplier/s profit, R&D and warranty. We expect industry capacity to grow by 10x over the period 2018-25E. As capacity doubles, the cost of labour and equipment goes up almost proportionally once utilization levels exceed 90%.

Figure 68: Battery cell cost breakdown ($/kwh)



Source: UBS Evidence Lab

Who will be the winners in the battery cell space?

Tim Bush
Asia Oil Refining and Chemicals

Taewoo Lee
APAC Tech

Kenji Yasui
Japan Conglomerates (Industrials and Consumers)

Paul Gong
China Autos

Lachlan Shaw
Global Commodities Strategy

We expect LG Chem, Panasonic, Samsung SDI and CATL to control 80% of the market by 2025. The fact that it takes a decade to move from the lab to production, plus incumbents' long commercial production track record, plus the cost benefits of scale, together constitute an almost insurmountable barrier for new entrants. According to Total Battery Consultant, it takes 10 years or more to move from the lab to commercial production. Safety is a key consideration for OEMs when selecting battery cell suppliers. Incumbents such as LG Chem have decades-long track records in EV battery mass production, free of any safety incidents. When new entrants come to market in 2020, most incumbents will have passed the 50GWh capacity mark. We further see incumbents going below US$100/kWh at cell level by 2021/22 with more advanced battery chemistries. Additionally, incumbents have already taken strategic equity stakes in upstream resources such as lithium and have entered into long-term contracts. We believe this will result in further savings on materials. Finally, the execution risk of increasing capacity for existing players is much lower as they are largely replicating existing production lines at established sites.

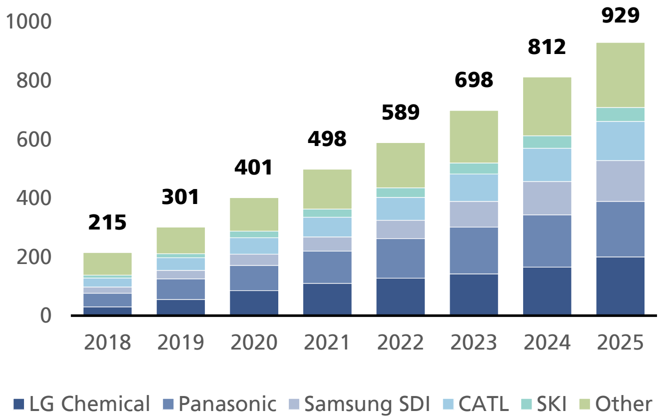
Oligopoly of existing leaders is most likely

Overall, we do not expect the competitive landscape for batteries to change significantly, as the likelihood of success for new entrants or other smaller players looks low absent an unexpected technological breakthrough. By 2021, we think the capacity of each of the top five producers will exceed 50GWh. We believe this implies almost insurmountable cost barriers for new entrants. With final investment decision (FID) today, they would likely be just reaching commercial production for their first 2-5 GWh production line by then. We expect Panasonic, LG Chem, Samsung SDI, SK Innovation and CATL to still be sharing ~80% the global EV battery cell market on a 5- to 10-year view.

18 new Gigafactories needed

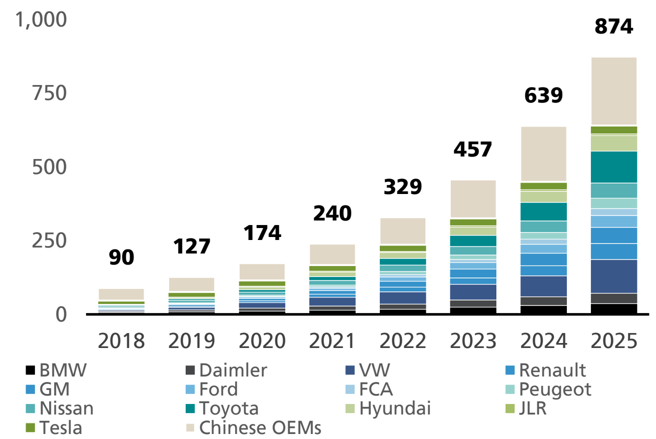
As the following charts show, cell capacity is likely to keep pace with growing demand over the next few years. Visibility on supply growth decreases after 2021, but we do not see cell capacity as a potential bottleneck. Our 2025 EV demand forecast would require the equivalent of 18 Gigafactories added globally.

Figure 69: EV battery cell supply… (GWh)



Source: UBS estimates

Figure 70: …and demand by key players (GWh)

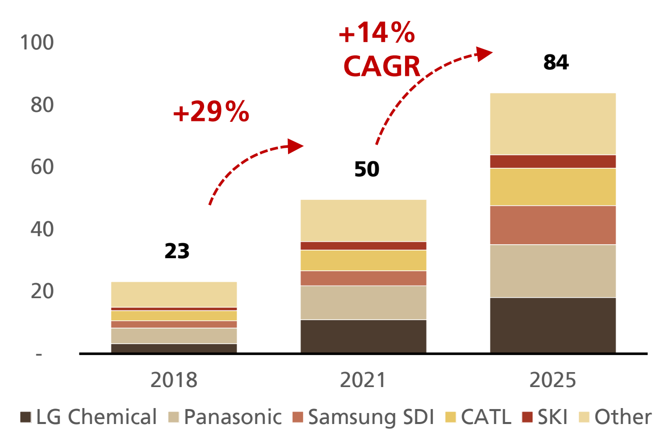


Source: UBS estimates

In spite of its cost leadership, Panasonic is likely to lose share to its competitors over the next few years, in our view, as neither global incumbents nor Chinese players are likely to switch to NCA chemistry (given the higher pack complexity and the more difficult thermal management). It is not even clear if Panasonic will fully track Tesla's growth path, as Tesla might partner with a local Chinese cell producer for its new Chinese car plant. We see LG as the biggest relative winner of market share.

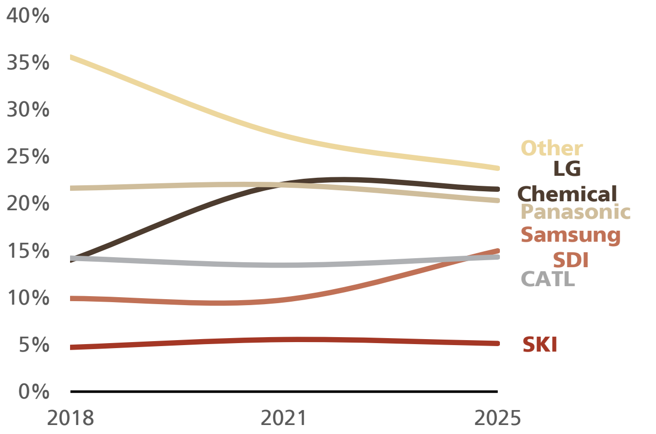
Panasonic is likely to lose share to its competitors while LG is likely to win

Figure 71: UBS battery market revenue forecast ($bn)



Source: UBS estimates

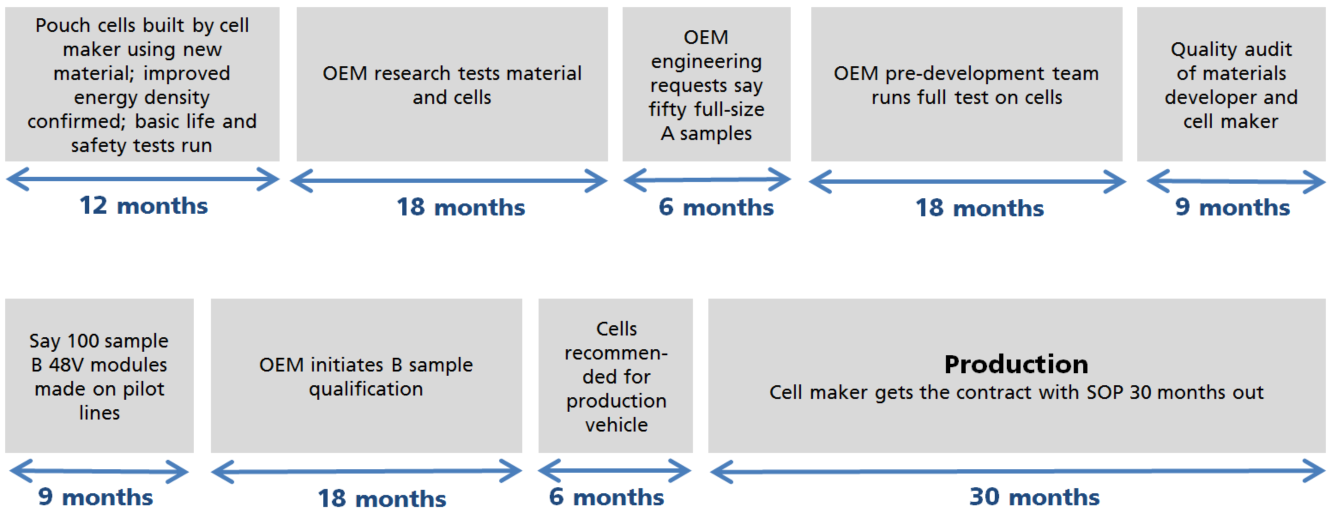
Figure 72: UBS global battery market share forecast – an oligopolistic market structure is most likely



Source: UBS estimates Note: Includes non-auto Li-ion battery markets

The figure below explains in detail how long it takes for a new entrant to launch a new greenfield operation. Given the high quality requirements in the auto industry, extensive testing and validation is required before a carmaker would enter a large-scale contract. At the very least, we expect this process to take ~4-5 years in total.

Figure 73: Long process from new material to production

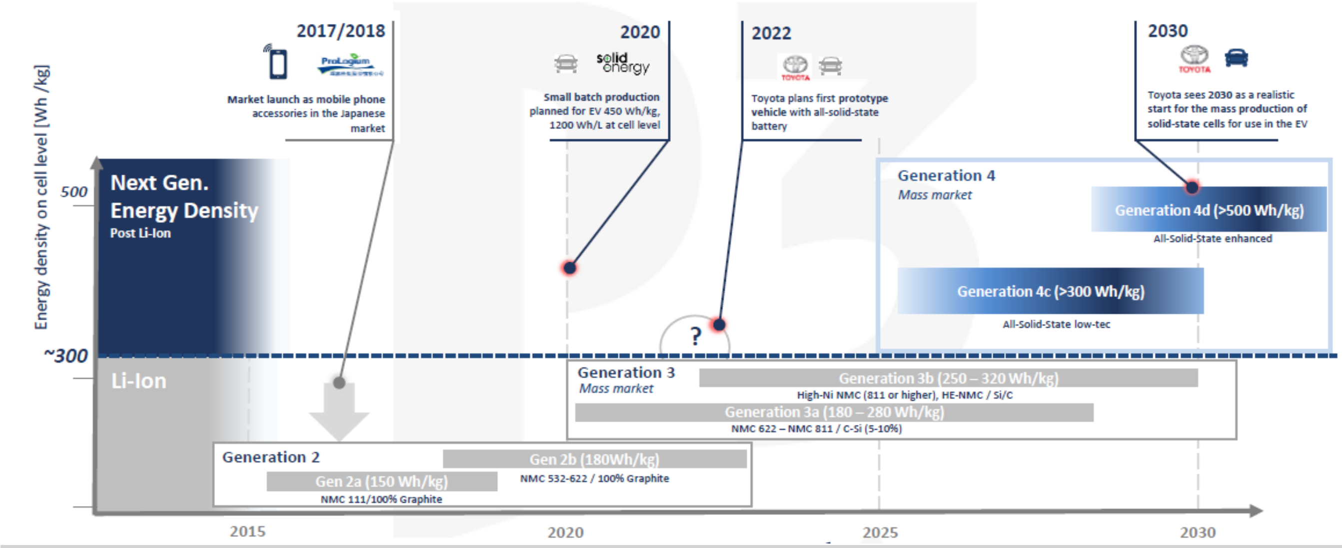


Source: Total Battery Consulting. UBS. Note: In many cases, some processes will overlap to some degree

Long-term outlook: Will solid-state batteries ever become a reality?

Solid-state batteries very different to Li-Ion batteries not only in the materials used but also in the production process. New production equipment would be required. The key advantages would be the higher energy density and faster charge times. However, the battery experts from P3 believe that scale production is at least another ~7 years or so away. Bringing the technology from small samples to large-scale automotive grade manufacturing is the biggest challenge, and as discussed, the validation of the technology will also take several years. We think that the era of solid-state batteries remains highly uncertain. However, we think the technology is not a must to reach cost parity between EVs and ICE cars, as optimized versions of the existing Li-Ion batteries will already get us there. In light of the low technology disruption risk with a 2025 view, we feel even more confident to say that today's battery leaders will also be the leaders in 2025.

Figure 74: Solid-state batteries in automotive not until 2025-30



Source: P3

Battery management system – why it makes such a difference

Kenji Yasui
Japan Conglomerates (Industrials and Consumers)

Tim Bush
Asia Oil Refining and Chemicals

Taewoo Lee
APAC Tech

We believe Tesla's battery management system (BMS) is the most sophisticated on the market: (1) it is updated regularly over the air to optimize performance; (2) it is able to control a high number of relatively unstable small battery cells (which are the cheapest on the market), hereby creating a competitive edge for Tesla and an entry barrier for competitors to use NCA chemistry. The superior performance is evidenced in very low battery degradation. Vertically integrated development capabilities will likely be the differentiating factor in EV battery development, since companies will be required to devise optimized overall designs to maximize system performance as a whole.

Various battery attributes can be exploited by changing the combination of the anode, cathode and electrolyte materials that constitute a battery. No 'perfect' battery exists. Consequently, all the battery formats end up with lower energy density if the emphasis is on safety or with higher costs if the emphasis is on weight, so there is inevitably a trade-off between elements, such as capacity, safety, weight, voltage/current density, and costs, according to the option selected. Thus, we feel designs will need to maximize the features prioritised in the system as a whole, while also optimizing the overall system to compensate for the features that have been sacrificed as lower priority.

One current issue facing EV penetration is vehicle range, and Tesla has differentiated itself in this respect

Our view, in light of our Model 3 teardown, is that the defining feature of Tesla's BMS is a design that makes the fullest possible use of deep learning and AI. The company has installed a large number of small batteries, and we believe it is capturing Big Data from actual driving data, and reinforcing its BMS algorithm through AI strengthened with deep learning. As a result, Tesla's battery lives are comparatively long. One current issue facing EV penetration is vehicle range, and Tesla has managed to differentiate itself in this respect. We think the company's strengths inherent in adopting pioneering design concepts are visible in this.

The Model 3's battery management system (BMS) has the following five key physical attributes:

(1) The system assembles 4,416 small low-capacity batteries to create a 75kWh system, rather than using pouch batteries with high capacity per unit.

(2) Tesla has designed its own semiconductors and software as the key elements in precise management.

(3) It takes a two-stage approach to cell-balancing, which is important in serial connections.

(4) NCA batteries' weak point is their relative flammability, but the design compensates for this weakness by using materials that conduct heat poorly and building in thermometers.

(5) Tesla can accumulate all data relevant to BMS infrastructure, including driving, charging, battery temperature, and battery capacity changes.

Advantages of such attributes are as follows:

(1) For several EV models in the market so far, battery capacity falls to less than 80% of the purchase date capacity after ~4-8 years, but most Tesla vehicles stay above 90%. The pace of degradation is also slow.

(2) The design assumes a degree of battery failure to start with, and defects have little impact. This system accepts errors rather than the traditional design approach, which regards them as 'unacceptable,' giving a high degree of risk tolerance.

(3) The system can be tailored to the differing requirements of sedans, trucks, sport cars, SUVs, and other vehicle types through varying configurations of the same batteries.

(4) Even though NCA battery materials are more flammable, using Big Data can create an operating environment in which it is hard for metal deposits to form or temperatures to rise. This also reduces the safety margins that normally apply, and increases capacity right to the limit even for batteries with the same capacity.

(5) Differentiation in cell balancing technology will become important when solid state batteries are adopted. The technology used in the Model 3, such as the Tesla-designed control IC and software, and two-stage cell-balancing management, could become differentiating factors from here on.

(6) Tesla has developed hardware and software that enables precise control, putting it in a good position to handle changes in the market. It should be in a better position to react to the scale and speed of changes than rival automobile OEMs, which outsource to software and semiconductor companies.

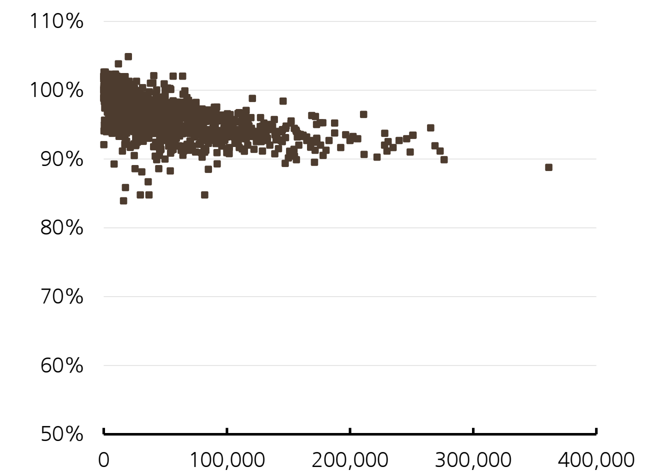
Tesla's long battery life is a result of its BMS

Capable of keeping battery capacity at 90% of the purchase date level even after five years' use

Tesla vehicles' battery specifications compare outstandingly with those of EVs already on the market, in our view. In particular, the slow battery degradation is a conspicuous difference: Tesla vehicles to date have kept battery capacity above 90% of the purchase date capacity even after 200,000-300,000km or four to five years on the road. This long-lasting battery capacity has developed into a differentiating factor for Tesla vehicles.

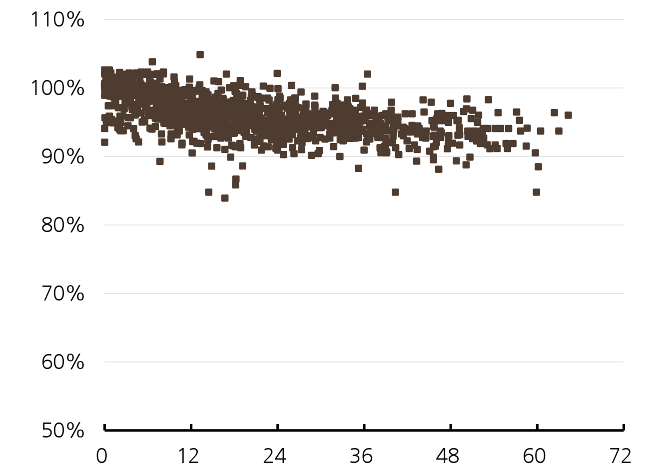
Figure 75 and Figure 76 below show data compiled voluntarily about driving and residual battery capacity by Tesla vehicle owners (Model S). Figure 75 shows the cumulative distance driven on the horizontal axis and changes in battery capacity on the vertical axis. Taking capacity at the purchase data as 100%, this falls to 90-95% after reaching 100,000km, but remains above 90% even after 200,000-300,000km. Figure 76 similarly shows data for battery capacity changes over time elapsed after purchase. Although this also shows just about a straight-line fall, the rate of decline is slow. By comparison, Nissan Leaf batteries, a model known for its high battery degradation due to a less sophisticated pack design (no liquid cooling), clearly degrade faster.

Figure 75: Distance driven (x-axis, km) and battery max capacity (y-axis,100% at the purchase)



Source: Dutch-Belgium Tesla Forum, UBS

Figure 76: Elapsed time after purchase (x-axis, month) and battery max capacity (y-axis, 100% at the purchase)



Source: Dutch-Belgium Tesla Forum, UBS

Countless small batteries on board

Tesla's distinctive feature is that it has packaged together a large number of small, cylindrical batteries. The system is designed to use software to precisely manage the minute differences in cylindrical batteries' performances, based on statistical data, providing equilibrium for the system overall. The Model 3 we pulled apart in our analysis had a hefty 4,416 batteries on board. We think this design with its large number of batteries feeds through to Tesla vehicles' strengths. The advantages of assembling a large number of small batteries include: (1) making it easy to stabilize battery performance as an entire system; (2) the ability to respond flexibly to future changes in designs and materials; and (3) the ability to make up for the materials' negative attributes.

Philosophy is to accept defects but keep the incidence rate constant, not eliminate them

We think Tesla's BMS design is pioneering in that it reflects a vision of maximally exploiting Big Data. Tesla's design concept is to allow for mistakes. The design presupposes that errors and defects will occur at the same rate in a system fitted with a large number of the same component, and is devised to mitigate the impact of such defects and reduce the degree of deviation in the defects themselves. By contrast, the conventional design concept is that 'mistakes are unacceptable.' The philosophy espoused by automobile manufacturers and the manufacturing industry to date has been to reduce this defect rate as far as is possible.

The greater the number, the smaller the deviation

Controlling a large number of units may look challenging, but, statistically speaking, it can readily reduce the range of deviation. For example, let us assume that 1% of batteries carry the defect of extremely low current due to production quality problems (the conventional business model seeks to reduce this to 0%). Ten low-volume systems with 10 batteries in each would use 100 batteries. There would be no problem with nine of these systems, but one of the 10 battery units in the system containing a faulty unit would be defective, with a fatal problem amounting to 10% of its total. The problem would become even more severe if two defective batteries were included. However, on the other hand, a high-volume system with 1,000 batteries already presupposes that each system contains 1% or 10 defective units in its design. The variation would be only 0.1% overall even if nine or 11 units were defective. It is easier to ensure safety with a high-volume system than with the above 10-unit system in which a one-unit change has a big impact. Furthermore, a system with 1,000 units would have to contain 100 defective units to suffer the same 10% impact as the above system with 10 units.

Deep learning finds conditions for this same incidence ratio and the correlation, while AI accurately reaches the closest possible decision, based on this incidence ratio derived from the correlation. Batteries are devices that store and release energy using chemical reactions and the laws of physics. The accuracy of chemical reactions and the laws of physics are verified by statistical experiment data. We think there is a good chance that the battery management system preferred by Tesla cars shows the future for BMS.

The approach of managing deviation is well-suited to deep learning

Tesla's pack has more than 10x more cells than NMC

EVs need high capacity, and all models' battery configurations are composed of a large number of individual batteries. Figure 77 compares battery configurations for Tesla (Model 3/S/X), Chevrolet (Bolt), and Nissan (Leaf). The key feature at Tesla is the large number of batteries or, more accurately, the large number of batteries mounted in parallel. As Figure 77 shows Tesla cars have 3,000-8,000 batteries, compared with fewer than 300 batteries for the Bolt and Leaf, or less than a 10th or so. The difference is particularly noticeable in the number of batteries in parallel. Tesla has as many as 30-90 units in parallel against only three to four at the other companies. On the other hand, the number of batteries in series is broadly the same, at 80-96. Total capacity is the same, albeit Tesla uses a large number of small battery cells.

A lot of small batteries installed in Tesla cars

Figure 77: EV battery specs

	Capacity	Parallel	Series	Total cells (Parallel × series)
Model 3	75 kWh	46	96	4,416
	50 kWh	31	96	2,976
Model S/X	100 kWh	86	96	8,256
	85 kWh	74	96	7,104
	75 kWh	70	84	5,880
	60 kWh	60	84	5,040
Bolt	60 kWh	3	96	288
Leaf	40 kWh	4	48	192
	60 kWh	3	96	288

Source: UBS Evidence Lab, UBS

We think opting for a design with a large number of batteries opens the possibility for a business model in which systems can be supplied to different vehicle types or models with different battery capacities within the same vehicle type. Vehicle types currently on sale include the Model S, Model X, Model 3, and Powerwall. CEO Elon Musk has also said the company plans to start selling the Roadster sports car and the Tesla Semi heavy-duty truck in future. For example, we estimate the Tesla Semi's battery capacity at 600-1,000kWh (range of 300-500 miles on a single charge, power efficiency of 2kWh/mile, according to Tesla). We think the company will be able to flexibly change the number of batteries in parallel and series to suit various requirements, such as a focus on high power output or range.

Plans compatibility with a wide range of vehicle types using the same batteries

BMS using software and semis designed in-house

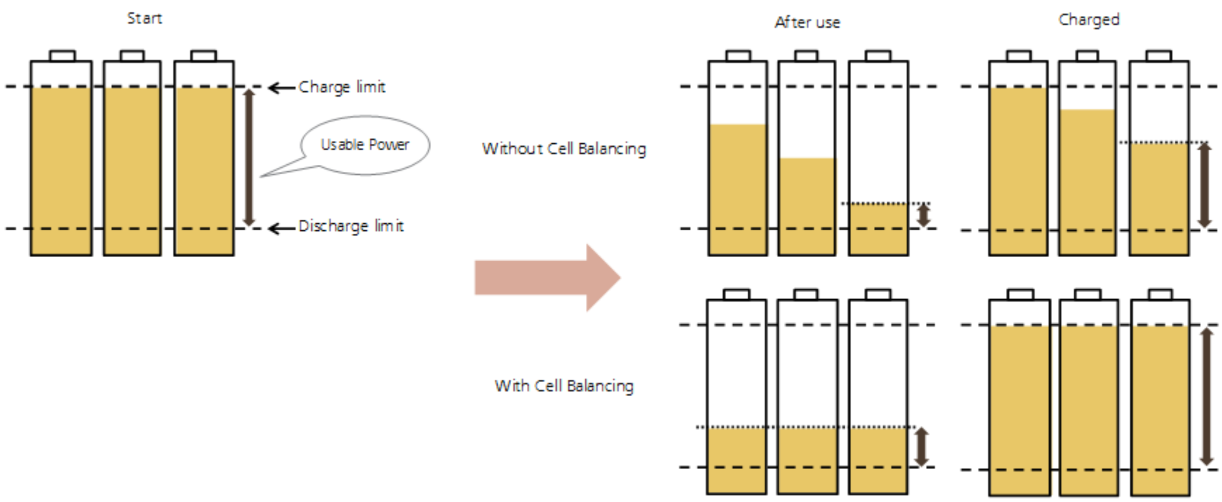
Voltage can be increased by connecting batteries in series. However, 'cell balancing', to maintain the same voltage in each connection, is important to mitigate battery capacity degradation. In the Model 3, there are as many as 96 bricks in connected series, and the current in these needs to be kept equal to the greatest possible degree. As an example, we consider a case in which the majority of bricks connected in series are 100% charged, while another brick is only 60% charged (Figure 78, 'after use'). Charging energy is applied to all 96 bricks broadly equally, and it is impossible to target the 60%-charged brick alone. Continuing to charge the fully-charged bricks could create heat owing to a current overload, leading to a fire. Consequently, once one is fully charged, recharging has to stop even if the others have not reached 100% (Figure 78, 'after charged'). Consequently, so-called 'cell balancing', to monitor each brick's charging status and adjust between them to maintain equal electrical potential, is important.

Electrical potential kept equal by connecting all 96 units in series

Our latest teardown reveals that the Model 3 achieves precision cell-balancing at 2-3mV (Figure 79). The batteries used in the Model 3 are all 3.8V, while the potential electrical variation between the bricks with their 46 batteries connected in parallel is a mere 2-3mV or 0.05-0.08% (=2-3mV/3.8V). This is the level of precision required of EV battery packs, and while our analysis is insufficient to determine whether Tesla has achieved higher precision than its rivals, this does not change the fact that it has attained highly precise control.

Model 3 electrical potential deviation held down to a mere 0.05-0.08%

Figure 78: Cell balancing



Source: UBS

Increasing the number of cells connected in parallel leads to a corresponding increase in battery capacity. The large number of battery cells groups in parallel also distinguishes Tesla sharply from other firms. The voltage among the batteries connected in parallel is automatically brought into line, obviating the need for the detailed control such as the abovementioned cell-balancing for series connections. However, the bigger the variation in battery performance parameters, the easier it becomes for degradation to progress. The small variation in the battery capacity/internal resistance of the batteries connected in parallel may contribute to Tesla car battery capacity's relatively slow degradation.

Battery variation needs to be reduced in parallel connections

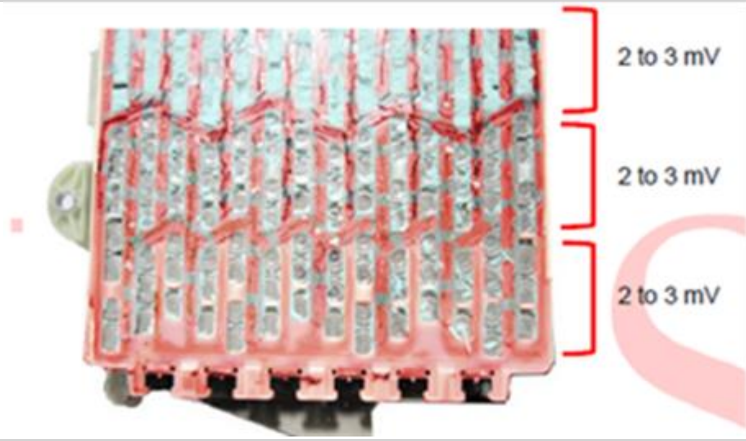
The way in which deviation in performance parameters between batteries connected in parallel leads to battery capacity degradation in assembled batteries is set out below. The minute variations in performance parameters (internal resistance: the battery's own resistance value) when cells are connected in parallel lead to current flowing back and forth between batteries, charging each other up, and causing them to go flat. The speed at which each individual battery degrades also varies even if functions were exactly aligned when new, degrading fastest close to the charging device or a heat source. Degradation increases internal resistance and gives rise to heat, in turn causing further degradation, causing the neighbouring battery to degrade as well.

Electrons can come and go freely in parallel connections

We think Tesla measures the attributes of countless batteries before assembly, selects those with very similar profiles, divides them into groups and then assembles them. In this way, it can leverage the benefits of manufacturing small batteries in high volumes, as problems inherent in variations can ultimately be substantially mitigated by testing the batteries and assembling those with the same performance attributes, even if some deviations emerge at the manufacturing stage. It is easy to imagine that deviations can be considerably reduced if already high-quality Panasonic-made batteries are inspected and categorized according to performance attributes.

Grouped into batteries with very similar attributes before assembly

Figure 79: Deviation between bricks is only 2~3mVa



Source: UBS Evidence Lab

Tesla designs both the hardware and software for its battery management system in-house. The Model 3's key features are: (1) Tesla itself designs the current management ICs; (2) it uses two-stage battery management; and (3) it controls temperature at the individual module level. Furthermore, in light of the above, we believe it compiles statistical data on factors such as temperature, voltage, and battery degradation speed, and uses deep learning at its own data centre to strengthen its management algorithm.

Tesla designs key technology itself

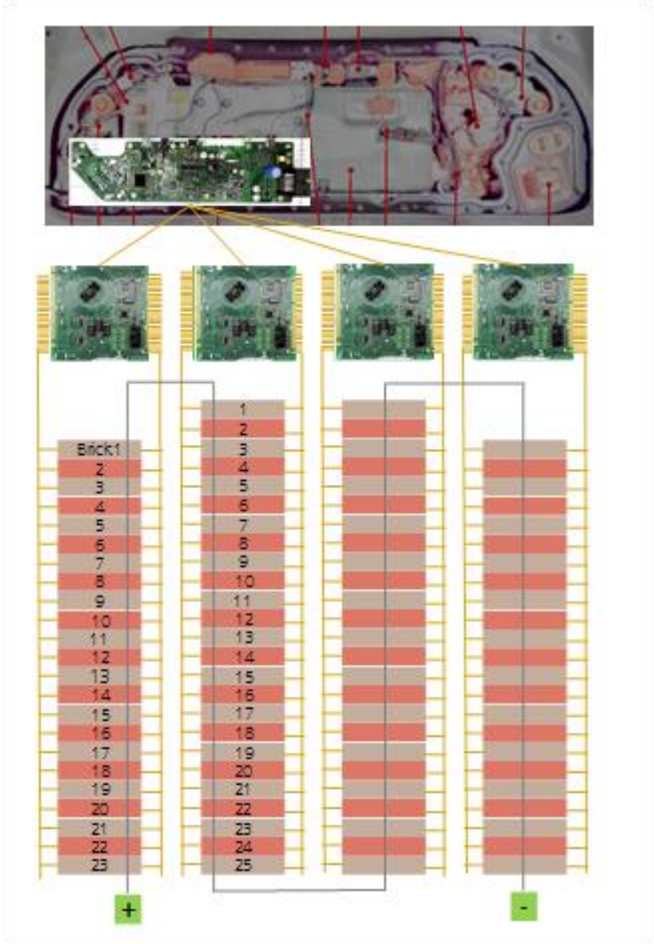
Figure 80 shows a Model 3 battery pack detached from the vehicle body and photographed from above. Figure 81 shows the BMS circuit, showing what peripheral components are connected to the battery pack. There are 23-25 bricks in each of the four large modules, which are each fitted with PCB substrates onto which semiconductors and electronic components are mounted. The PCB substrates are connected to the high-voltage controller installed on top. The high-voltage controller is built together with elements such as the OBC (on-board charging), which controls the step-down conversion to 12V.

Composed of a high-voltage controller and four modules

Figure 80: Model 3 battery pack

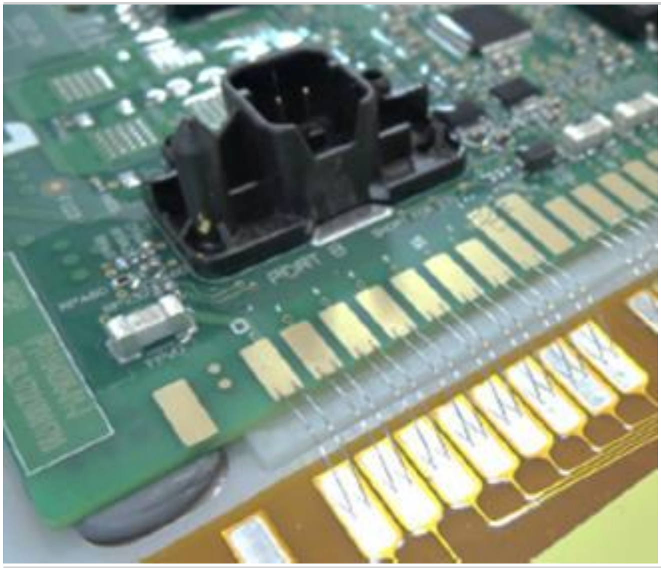
Source: UBS Evidence Lab

Figure 81: Battery and HV system controller in Model 3



Source: UBS Evidence Lab

Figure 82: Connecting terminal in BMS



Source: UBS Evidence Lab

Figure 83: BMS mounted on each battery module

Source: UBS Evidence Lab

There are 25 connecting terminals at either end of the PCB substrate on the module (Figure 82, Figure 83, Figure 84, Figure 85), and the wires running from these terminals reach the assembled battery. The uppermost terminal coming from the left of the PCB itself connects to the left-hand side of Brick 1, while the uppermost terminal coming from the right of the PCB connects to the right of Brick 1. We believe the potential difference between the left and right sides is measured, enabling a clear picture for each brick. There are 23 of this type of connection on the outer modules and 25 on the inner modules, and we think the potential difference is being measured for all 96 bricks connected in series.

We estimate that current is controlled at the individual brick level within the modules

The PCB substrates connected to each battery are shown in Figure 84 (front) and Figure 85 (back). The control ICs designed in-house by Tesla are shown as the yellow stars and green circles in Figure 84, confirming that two of each are mounted on the front surface. We think the reason there are two of each is also to ensure redundancy for safety. We believe the design is such that if one IC stops working, software management reduces the volume of operations, so the remaining IC can perform these over time

Redundancy ensured

Further interesting points include: (1) these in-house ICs are inscribed with the nicknames Batman and Robin on the control panel (Figure 86), and using a chemical treatment to remove the control IC's resin cover reveals a Model 3 stamp in yellow on top of the IC that emerges (Figure 87); and (2) Batman and Robin control ICs are mounted on both the PCB and high-voltage control fitted to each module. They are stamped in a way that trumpets the proprietary design, revealing self-confidence at Tesla and its development engineers.

In-house chips marked Batman and Robin

The roles of Batman and Robin are currently unclear in many respects. Our view is that Robin, which has a small zdie-size and only 38 pins, collects voltage/temperature analogue data and digitizes it, while Batman, which has a large die-size and a hefty 64 pins, uses the digital data sent by Robin to gauge charging status, govern cell-balancing, and share data/collaborate with multiple systems.

We think Robin collects data, while Batman handles most of the operations

Cell balancing within series connections uses active balancing to transfer electric power from cells with high electrical energy to those with low electrical energy. Each 'brick' with 46 cells connected in parallel is recognized as a single high-capacity battery in the cell-balancing process, while each brick is connected in series, and the potential difference between bricks is standardized. A lot of analogue devices are mounted onto the BMS board to temporarily store this electrical energy. On the front surface there are six inductors, 63 0805 capacitors, 23 0603 capacitors and 26 0402 capacitors, while on the reverse side there are 15 0805 capacitors, 10 0603 capacitors and 18 0402 capacitors. The teardown confirms that this kind of battery control consumes a large number of analogue devices, on top of MCU chips governing digital processing.

Many analogue components when using active balancing

Tesla may manage cell-balancing in two stages. First, cell-balancing is conducted frequently by Batman and Robin, mounted on the PCB substrates fitted to each of the four big modules. Next, one further Batman and Robin set, mounted on the high-voltage control panel, may carry out cell-balancing between the four modules. This two-stage management probably enables precise voltage control. The Batman and Robin set mounted on the high-voltage control panel is shown in the white box centre-left in Figure 88. Within the box, the yellow star pinpoints Robin and the green circle, Batman.

Two-stage cell-balancing: once at each individual module and again for modules overall

We estimate that the above two-stage control makes it comparatively easy to expand battery capacity. Adding modules does not alter the precision of cell-balancing, since each one is fitted with a BMS panel. We estimate that the Batman and Robin ICs mounted on the high-voltage controllers take care of integrated monitoring of the four modules. We do not see any great problem with central control to monitor/control four or more modules since the Batman/Robin ICs installed on each module monitor the status of 23 25 battery cells. For example, doubling the current 75kWh would be easy from the perspective of the system.

Battery capacity expansion fairly simply achieved by adding modules

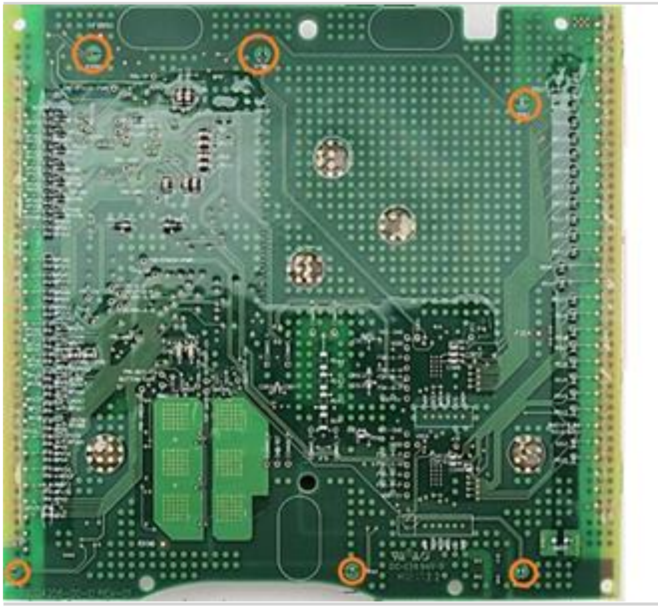
As the orange circles in Figure 85 show, six temperature sensors are mounted on the back of each module's PCB. This teardown alone was not enough to confirm which component the temperature sensors are connected to, and it is currently unclear precisely which battery component's temperature is being measured. However, batteries are devices that use chemical reactions in their internal materials, and the speed of the reactions is easily changed by temperature. Consequently, it is important to monitor and manage temperature, and the PCB substrate design confirms that care has been taken with temperature control in the Model 3, as well.

Battery temperature also controlled

Figure 84: BMS PCB (front)

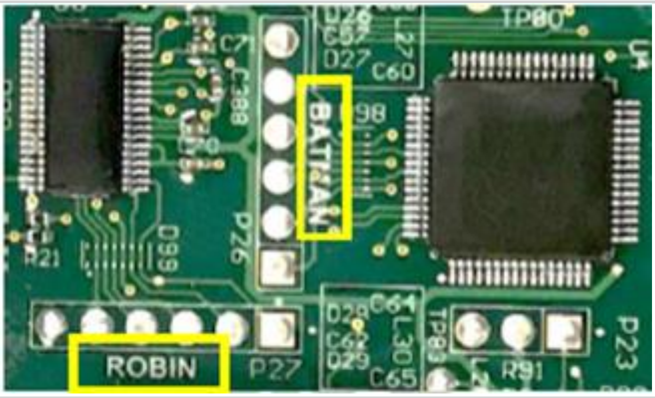
Source: UBS Evidence Lab

Figure 85: BMS PCB (back) – temperature sensor marked in orange



Source: UBS Evidence Lab

Figure 86: Robin and Batman ASICs

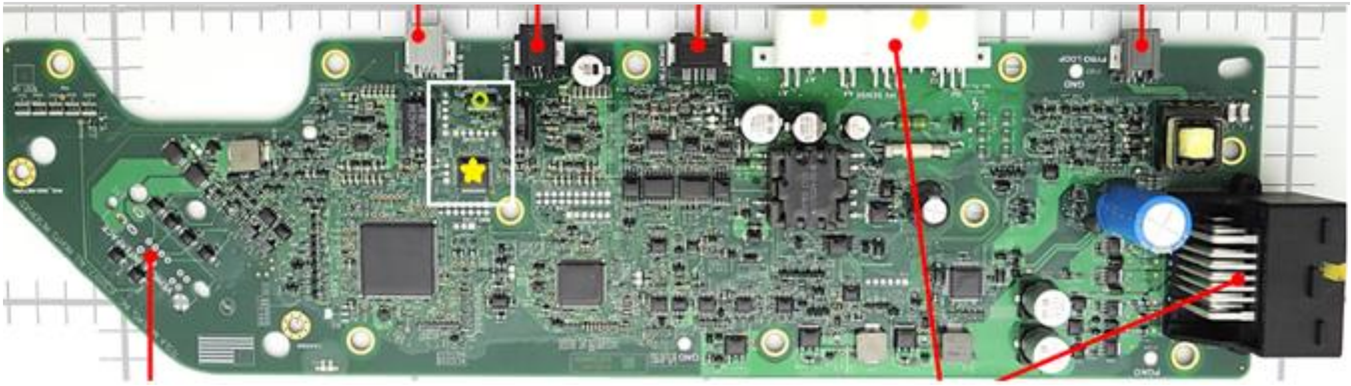


Source: UBS Evidence Lab

Figure 87: Robin and Batman ASICs without covers (etched in logos on the chips)

Source: UBS Evidence Lab

Figure 88: High-voltage system controller (marked Robin and Batman in white)



Source: UBS Evidence Lab

Comparison with Chevy Bolt

Many differences

There are five big differences between the Model 3 and Bolt: (1) the Model 3 uses semiconductor chips designed in-house, whereas the Bolt uses chips bought in from outside; (2) the Model 3 carries 18 battery management system MCUs, but the Bolt has more at 25; (3) there is no great difference in the value of MCUs fitted at US$72 for the Model 3 and US$84 for the Bolt; (4) cell-balancing on the Bolt is probably conducted in one stage, rather than the two-stage approach in the Model 3; and (5) the Bolt does not use a two-layer management system, and increasing capacity could impair cell-balancing accuracy, accelerating performance degradation. However, we estimate the semiconductor cost solely from the general calculation using factors such as the die size, while elements such as the proprietary design development expense are excluded. Consequently, there may be a big gap with the actual costs borne by Tesla.

Control panel suggests Bolt is centralised, while the Model 3 is distributed

The Bolt's BMS panel is centralized in a single location (Figure 89). This provides a good contrast with the Model 3's, whose control panel is distributed across five locations, namely, four at the modules (one each) and one at the high-voltage control panel. On the other hand, high-voltage control covers 96 units in both. In the 60kWh Bolt, three large pouch batteries are connected in parallel to form one brick, and 96 such bricks are connected in series (Figure 90). In the Bolt, four 10-

brick units and an eight-brick unit are lined up in a large silver box (Figure 90) and the battery is composed of 10 such boxes.

Bolt uses control ICs made by LG, which supplies its batteries

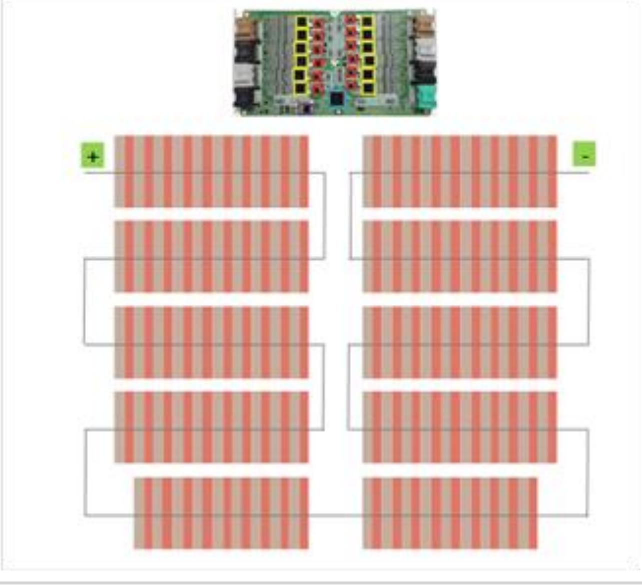
There are broadly three semiconductor ICs mounted on the Bolt control panel, noted below (Figure 91). We estimate the semiconductor cost of each at: (1) US$5/unit for LG/STM products; (2) US$1/unit for Freescale/NXP 8-bit MCUs; and (3) US$12/unit for 32bit-MCUs. Therefore, we put the cost at: (1) US$5 x 12 units; (2) US$1 x 12 units; and (3) US$12 x 1 units for a total of US$84.

(1) **Yellow-marked ICs in the middle of Figure 91:** Designed by battery supplier LG Chem and made by semiconductor manufacturer ST Microelectronics. Monitors battery pack voltage and temperature, implements cell-balancing commands at each battery, etc.

(2) **Red-marked ICs in the middle of Figure 91:** Freescale/NXP-made 8bit-MCU. Calculates estimated values, such as charging rates, voltage and current, from voltage and temperature data.

(3) **Blue in the middle of Figure 91:** Freescale/NXP 32bit-MCU. Conducts cell-balancing calculations/commands from battery data, communicates with systems other than the battery, etc.

Figure 89: Chevy Bolt battery cells and BMS

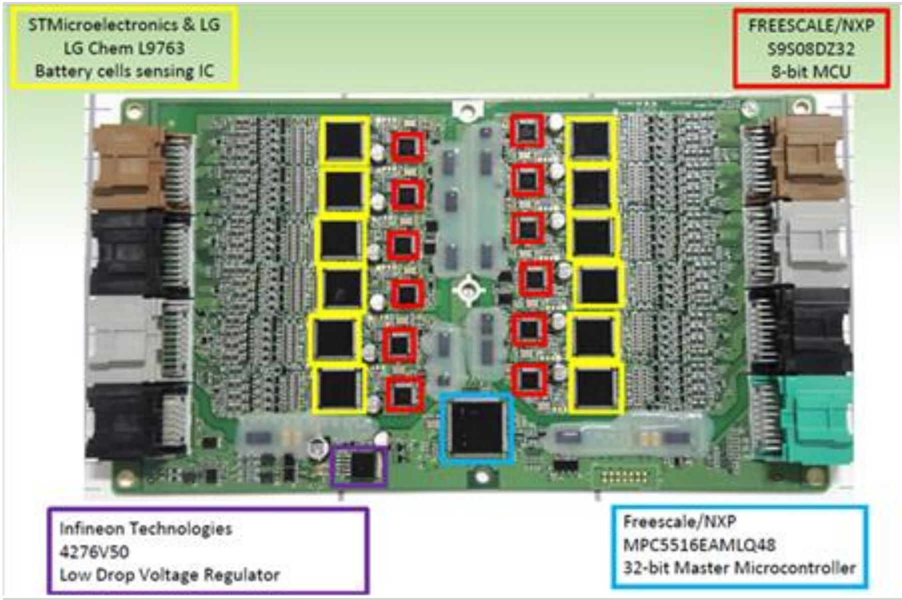


Source: UBS

Figure 90: Chevy Bolt battery pack

Source: UBS

Figure 91: Chevy Bolt BMS PCB



Source: UBS

BMS makes up for weaknesses in cell design

Configured so that strengths inherent as a system are renewed daily

Tesla's battery management system is configured so that the system as a whole compensates for weaknesses inherent in the specifications of the batteries used. The key attribute of Tesla's batteries is that they emphasise high-energy density in both materials and shape. Also, the configuration is upgraded on a daily basis over the air. Different batteries use different materials, so there are already great variations in battery specifications, depending on what materials are used. Furthermore, much can only be discovered about how overall system specifications change according to usage conditions by actually using them. Systems in which a large number of batteries are assembled are probably more prone to performance attribute differences than standalone batteries.

Tesla will likely be able to differentiate itself further when solid state becomes a reality

One of the most promising future battery material changes from a post-2025 perspective will likely be the shift to solid state batteries, which use solid materials for the electrolyte. At that point, the advanced technological capabilities in the aforementioned cell-balancing will probably be required. Solid state batteries are expected to bring plenty of positives, including: (1) reduced fire risk, due to the small amount of volatile materials in the composition; (2) higher energy density; and (3) the ability to incorporate the assembled battery structures of series and parallel connections within the cell. On the other hand, the fact these are solid state makes them more prone to an increase in resistance to lithium-ion transport, while cathode and electrolyte interface resistance also increases, leading to greater internal resistance than with lithium-ion batteries. High internal resistance can easily give rise to differences in battery capacity for batteries connected in series, so advanced cell-balancing technology will be required.

Charging facilities, chargers, control ICs, management software etc. all developed in-house

Tesla has outsourced production of the small battery cells to Panasonic, but apart from that, it has built up the battery management semiconductors, software and charging equipment infrastructure through proprietary designs, accumulating data in the process. It has collated battery data, including capacity, temperature changes and charging conditions, as well as on-the-road data, such as acceleration, braking, and external temperatures, and we estimate that it combines these to

build statistically efficient battery management algorithms. It installs recharging Superchargers designed in-house, and we think this enables it to find more efficient charging methods, control temperatures precisely, and extend battery lives. To recharge batteries, Tesla uses chemical reactions to transport electronics from an ionized substance within the battery. Electron transfer becomes difficult at low temperatures, slowing the charging speed, while electron transfer becomes violent, resistance increases, and the danger of fire escalates when the temperature is too high.

Can also use large data-centre knowhow

Tesla supplies storage battery systems to AWS data centres. Tesla may have been able to gear up its battery management capabilities from having these in use at Amazon data centres. James Hamilton, who is responsible for building Amazon data centres, has mentioned plans to build a massive 4.8MWh storage battery system for its own data centre in California, co-operating with Tesla. Power consumption behaviour for components such as CPUs, DRAMs and air-conditioners is being managed via Big Data at data centres – not just the storage battery system. Tesla already has considerable experience of running efficient data centres through AI management, reinforced by deep learning from this huge reservoir of data. This kind of large-scale data centre management may allow Tesla to swiftly acquire algorithms involving new ideas and state-of-the-art technologies not available through automobile driving data alone.

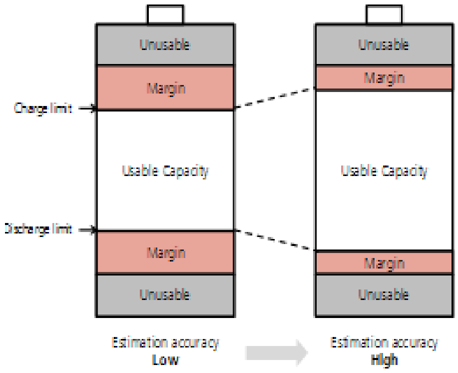
May be able to achieve greater capacity than rivals even with the same battery

Tesla has achieved precise management, and it may also be able to increase capacity available in charging/discharging by reducing the safety margin. Battery management entails collecting battery charging/discharging data. We estimate that the company owns statistical data on battery performance, leveraging this Big Data. Over-charging/discharging batteries can cause lithium-ion deposition that changes the external shape of the battery or give rise to excess heat, making it impossible to maintain safety. Consequently, charging/discharging behaviour is designed to maintain a safety margin before batteries are over-charged or over-discharged. The more precisely this charge/discharge can be controlled, the smaller the allowable safety margin and the greater the usable capacity can be.

Has already achieved temporary capacity increase through software management

Indeed, when Hurricane Irma struck the Florida peninsula in September 2017, Tesla provided a free wireless upgrade to vehicle owners in the affected region that temporarily increased battery capacity and extended vehicle range. This boosted Model X and Model S battery capacity from 60kWh to 75kWh and added 48km to the range. We believe that Tesla changed the programme to allow batteries to be discharged right up to the limit by removing the safety margin (though still setting this so that it could not reach zero).

Figure 92: Charge and discharge margin control



Source: UBS

Tesla's battery pack weaknesses

Safety (incidents of fire in the past)

Materials are relatively flammable

A number of accidents have occurred with Model S/X vehicles to date, and it has already been confirmed that fire expands if it spreads to the battery. This is because NCA's basic problem as a battery material is that it easily combusts. In the Model S/X, the space between batteries is filled with liquid glycol as a heat-conductive material. In the latest Model 3, the batteries are all held in place with a flame-retardant material. Therefore, we think it has been tweaked to make it harder to burn than the prevailing Model S/X.

Harder to provide maintenance service

No problem even if multiple batteries fail

All of the countless batteries installed in Model 3s are connected with a fire-retardant adhesive. Consequently, we think partial battery replacement is difficult. We pointed this out in our report, Lap 3: Fit & Finish, as well. However, 4,416 batteries are connected in the 75kWh model, composed of 46 in parallel x 96 in series. There is no system-level problem even if several of these batteries fail, and there is no need for immediate replacement. This is because changes in the number of batteries connected in parallel change the battery capacity, but not the voltage that needs to be managed. Even if, say, 10 of the 46 batteries connected in parallel were to prove defective, leaving only 36 in parallel, there would be no great alteration in current and voltage in terms of the battery performance profile.

Whole module has to be replaced, likely making this expensive

If one part alone is damaged in an accident, for example, the whole battery module would need to be replaced, not just the part itself. The Bolt uses 10 modules, while the Model 3 is configured with four, so replacing the Model 3 module is likely to be significantly more expensive.

Increased power loss risk

Electronic control does not work if power is lost

Our teardown confirmed Tesla vehicles' outstanding electronic control technology. The design involves gathering all kinds of data and increasing performance by achieving a good balance as an overall system. However, it may become hard to activate safety functions or temperature control in the event of a brief power source failure or a temporary electricity supply interruption from the power source due to a defect.

Cybersecurity

Malware poses problems when sharing software

The problem of cybersecurity will expand as vehicle communication networks become more advanced. The risks will also mount as software development increasingly is shared by leveraging avenues such as open software. Malicious software invading the communications network could rewrite battery management system programs, stop them from working, suddenly change battery capacity, or lead to batteries becoming distorted or catching fire.

Appendix

Manufacturing process deep dive: Electrode – cell assembly – formation

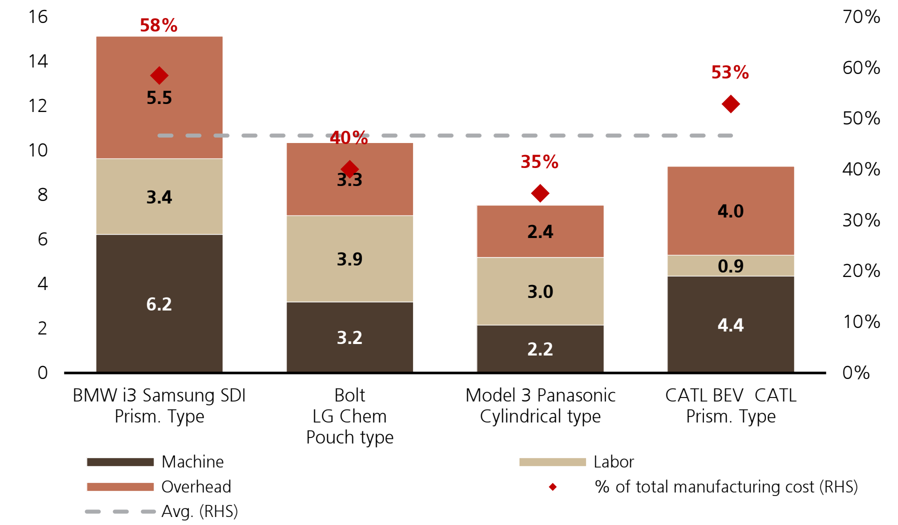
We separate the manufacturing process for prismatic, NCA and pouch cells into three stages: electrode manufacturing, cell assembly and formation.

1. Electrode costs: cylindrical < pouch < prismatic

Electrode stack is referred to as a jelly roll

The electrode, which consists of the cathode and anode, and the manufacturing process are identical for all three formats. The production process includes mixing, coating, drying, calendaring and slitting. Differences in electrode production costs largely come down to differences in scale, labour costs and energy density. The production of the electrode is the most labour-intensive step of the cell manufacturing process. The electrode stack is referred to as a jelly roll. The jelly roll consists of alternating layers: separator-cathode-separator-anode.

Figure 93: Total electrode costs (US$/kWh)



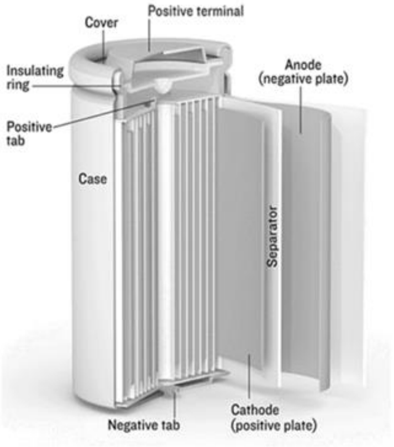
Source: UBS Evidence Lab

Manufacturing advantages of cylindrical cells

Cylindrical cells offer the most efficient space utilisation but…

The cylindrical cell format uses a single jelly roll that is continuously wound into a round aluminium housing. The size of the housing is slightly larger than a standard AA battery. A continuous jelly roll allows for efficient space utilisation in the cell, as: (1) there are no voids; and (2) electrolyte usage in reduced.

Figure 94: Cylindrical NCA format and jelly roll



PANASONIC	Total cell dimensions:	69.5 x 21 mm *(l x d)*
	Weight:	68.5g

Source: UBS Evidence Lab

Cylindrical cells also have disadvantages

…this comes at cost in terms of assembly, cell management and safety

The cylindrical cell format is by far the smallest and lightest relative to other formats. A Panasonic cell is only 17.52Wh per cell, versus 219Wh for LG Chem's pouch format. Consequently, the number of cells needed for a battery pack using this format is significantly higher. For example, the Model 3 requires 4,416 cells for the 77kWh battery pack, versus only 288 cells for the Chevy Bolt's 63kWh battery pack. More cells increases pack assembly complexity (hooking all the individual cells together). Additionally, a more sophisticated battery management system is required to control the cells. More cells also means there are more places something can go wrong. This increases the safety risk of the cylindrical format.

Current interrupt device (CID) is a safety feature of cylindrical cells

Panasonic's cell lacks the CID safety feature

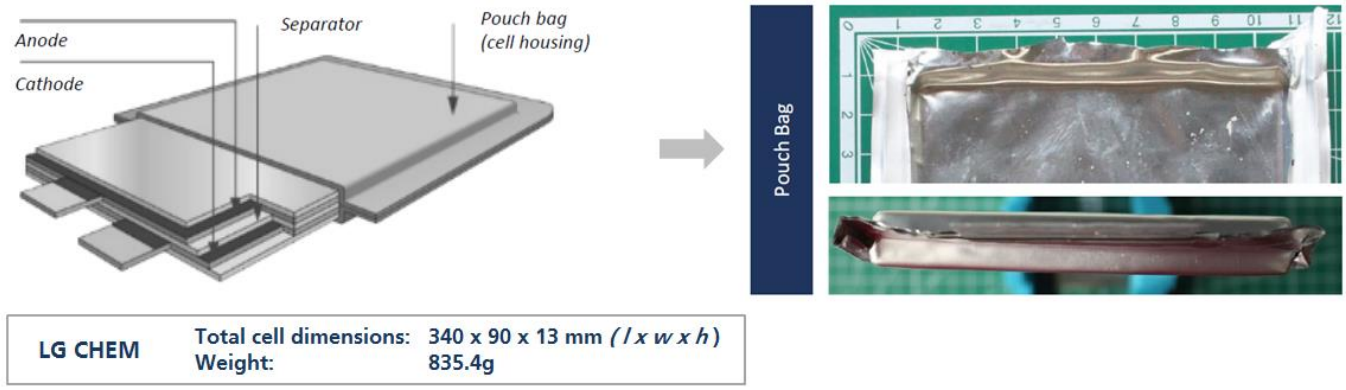
The CID is a sophisticated vent that cuts off the current and prevents thermal runaway. It is generally used in cylindrical batteries because of their high energy density. Cylindrical cells would be an ideal solution if the cell size could be significantly increased. However, Arc is generated in the open CID when voltage is increased, and this results in battery fires. The key limitation of cylindrical batteries is that it is difficult to increase the cell size further.

The pouch format also has a continuous jelly roll setup

Jelly roll stacking and folding increase manufacturing complexity

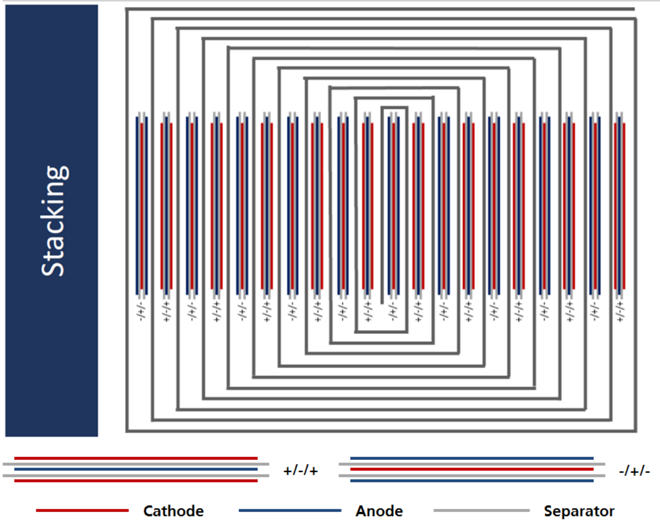
The jelly roll is stacked and folded (see below), and housed in a thin aluminium-polymer compound foil. The greater production complexity of stacking and folding the electrode results in a slower manufacturing speeds. Pouch batteries have better energy density than prismatic because they are lighter. The key downside of pouch format is that the cell lacks rigidity.

Figure 95: Pouch format and pouch bag



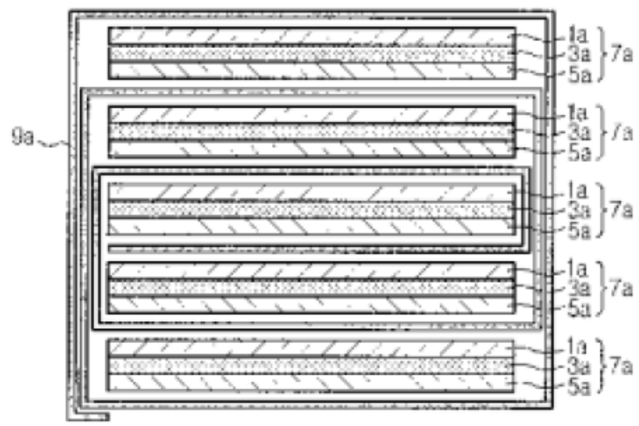
Source: UBS Evidence Lab

Figure 96: Stacked and folded in a patented process



Source: UBS Evidence Lab

Figure 97: Schematic cross-sectional view of a stack-folding type electrode assembly



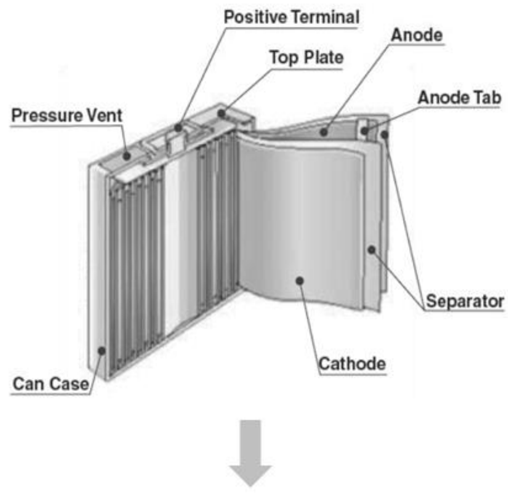
Source: UBS Evidence Lab

Prismatic cells use multiple jelly rolls

Safety focus of prismatic cells increases weight

For the prismatic format, multiple jelly rolls are inserted into a rigid aluminium can. The insertion of the jelly roll into the can, and the laser welding of the can, adds to the complexity/cost of the prismatic format production process. There are also more housing and safety features than is the case with NCA/pouch, which increases the weight and reduces energy density. It also tends to result in excess material such as cathode foil and electrolyte. In the future we may see a hybrid between prismatic and pouch batteries: the continuous jelly roll of the pouch battery would provide better space optimization, while the prismatic can would increase rigidity/safety.

Figure 98: Prismatic format and jelly roll



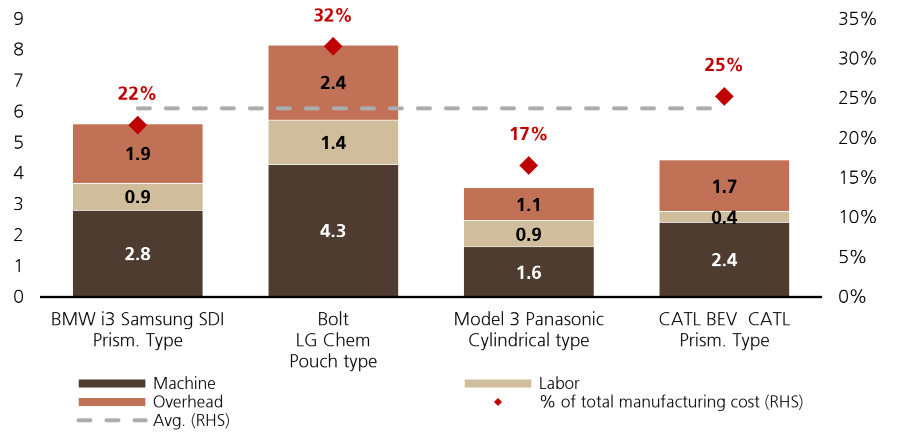
SAMSUNG SDI	Total cell dimensions: Weight:	173 x 45.5 x 125 mm *(l x w x h)* 2026.4g
CATL	Total cell dimensions: Weight:	147 x 25 x 92 mm *(l x w x h)* 809g

Source: UBS Evidence Lab

2. Cell assembly costs: cylindrical < prismatic < pouch

There are significant differences in the complexity of the cell assembly processes for the three formats, as is clearly visible when taking assembly as a percentage of total manufacturing cost: for cylindrical, prismatic and pouch formats, cell assembly accounts for 17%, 25% and 32% of total manufacturing cost, respectively. Cell assembly is simplest and least expensive for the NCA format, involving only two steps: electrolyte filling and cell assembly. All cell formats require these two steps. Prismatic and pouch cells both also require winding and welding.

Figure 99: Cell assembly costs by company (US$/kWh)

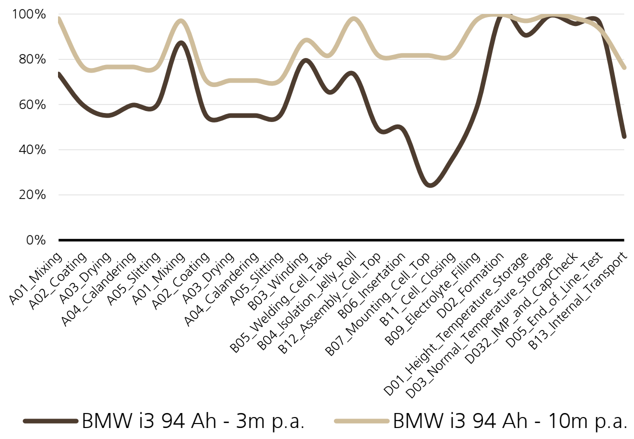


Source: UBS Evidence Lab

Cell assembly is a production bottleneck for prismatic cells

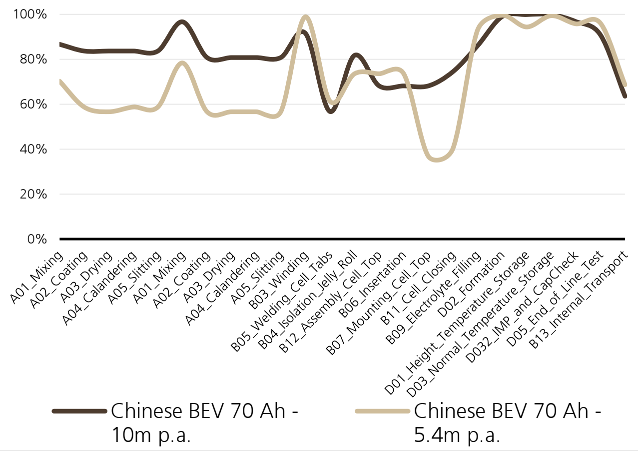
Additional steps in the prismatic process largely relate to manufacturing an aluminium can, inserting the jelly roll and then sealing (laser welding) the can. Specifically, these steps include isolating the jelly roll, inserting the jelly roll, mounting the cell top and cell closing. For both Samsung SDI and CATL these additional steps account for about a third of cell assembly costs. Additionally, as seen below, these steps create a bottleneck in the production process, with utilization rates for SDI and CATL falling below 40% at the jelly roll insertion step. See below.

Figure 100: Utilization rate for Samsung's prismatic cell



Source: UBS Evidence Lab

Figure 101: Utilization rate for CATL's prismatic cell



Source: UBS Evidence Lab

Pouch cells require three additional assembly steps

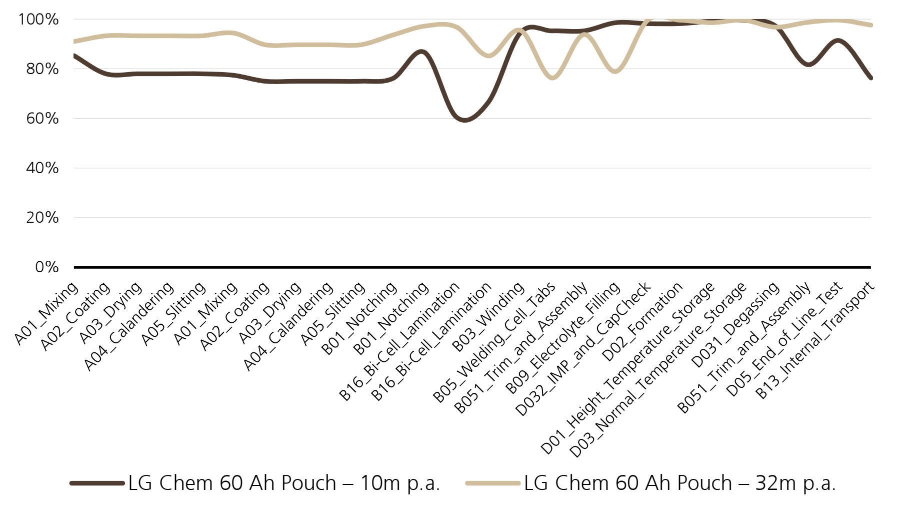
The pouch format has the highest assembly cost among all three formats. LG Chem's pouch format cell has 32 anode sheets, 31 cathode sheets and 43 separator sheets plus one continuous separator. Combining these sheets requires three additional production steps: notching, lamination and trim/assembly. The notching and bi-cell lamination required for the stacking process is time-consuming and lowers throughput relative to the continuously-wound jelly rolls for other formats. These additional steps account for 66% of the assembly cost. These steps are not labour-intensive (16% of total) and should be a key area of manufacturing cost savings as scale increases.

3. Formation costs: Prismatic < pouch < cylindrical

The final step of the production process is cell formation. For all formats, this process consists of formation, temperature storage, cap check, end-of-the-line testing and internal transport/trim assembly. For the pouch format an additional degassing step is required. The cylindrical cell format has the highest formation cost, which we believe is due to the greater number of individual cells required. For, example end-of-the-line testing cost is highest for the cylindrical format. The prismatic format is the lowest-cost format at the formation stage. Again, we attribute this to the individual cell size being larger. For example, end-of-the-line testing for prismatic format is US$1.70-1.90 per kWh, versus US$5.58 per kWh for cylindrical format. Put simply, more cells per kWh must be tested for smaller formats. The pouch format would also compare favourably if it were not for the additional degassing step, which adds US$1.94/kWh to the format's total formation costs and accounts for 26% of the total. This step, along with the

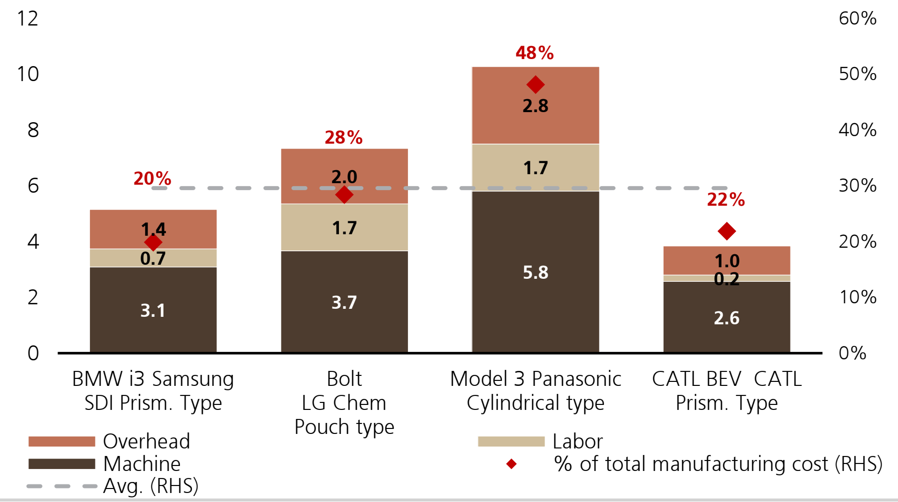
stacking and folding in the assembly process, is the key production bottleneck for the pouch format.

Figure 102: Utilization rate for LG Chem's pouch cell



Source: UBS Evidence Lab

Figure 103: Cell formation costs by company (US$/kWh)

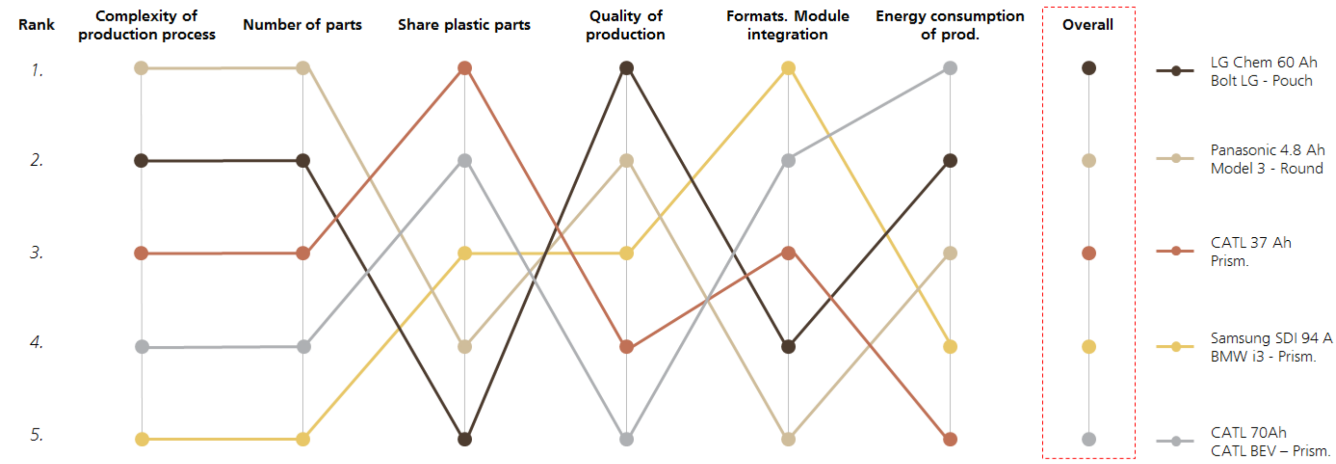


Source: UBS Evidence Lab

Manufacturing process differs by company

In comparing the manufacturing process by format, we have avoided discussing company-specific differences. However, for both the cylindrical and pouch format, we only had Panasonic and LG Chem's cells as point of comparison. For the prismatic format we can compare manufacturing differences between CATL and Samsung SDI.

Figure 104: Battery manufacturing & supply chain ranking



Source: UBS Evidence Lab

1. Panasonic's NCA cylindrical cell

Advantages: lowest cost and highest energy density

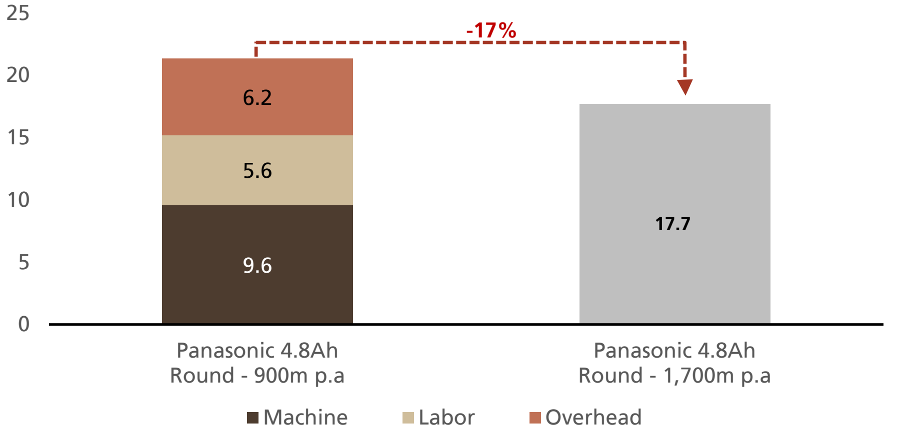
Panasonic uses the fewest components/sub suppliers and production steps, and has the highest utilization rates throughout the manufacturing process. The tightly wound continuous jelly roll allows for the highest energy density (W/hl). There is also a minimal amount of electrolyte use, as electrolyte was only found between the jelly rolls. Plastic parts only account for 0.4% of the total, the second-lowest among the four suppliers. Minimal usage of plastic parts is an indicator of production and design quality. The Panasonic ranks second in gravimetric energy (Wh/kg) after LG Chem, due to more housing material and a lower gravimetric loading for the cathode and anode. However, the low-complexity design of the Panasonic cell comes at the expense of safety. For example, unlike most cylindrical cells, Panasonic's cell lacks a CID (a vent that prevents thermal runaway and, ultimately, explosions). The Panasonic cell also lacks a positive temperature coefficient device (PTC), another safety measure.

Formation as key cost driver

Disadvantages: small cell size, limited scope for further cost savings and safety

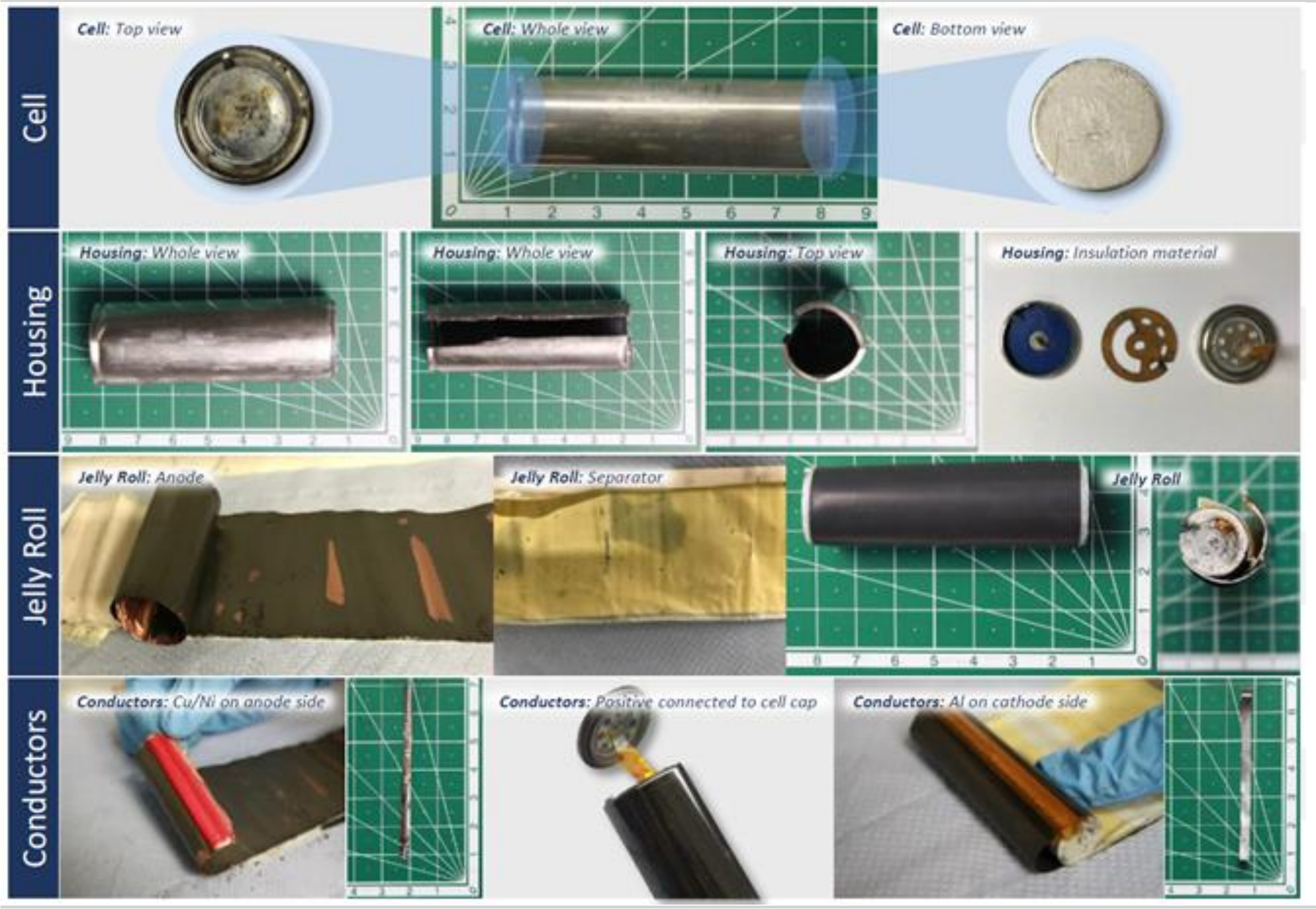
At 48% of total manufacturing costs, formation is a key cost driver, at US$10.27/kWh. For Panasonic, formation is both time- and investment-intensive. Due to the small size of the cells, the cost effect per kWh is higher for formation and end-of-the-line test as more cells per kWh need to be connected. The small cell size also creates packing and battery management system challenges. Finally, as manufacturing costs have already been minimized through economies, there is little further cost-saving through additional scale.

Figure 105: Panasonic manufacturing cost (USD/kWh)



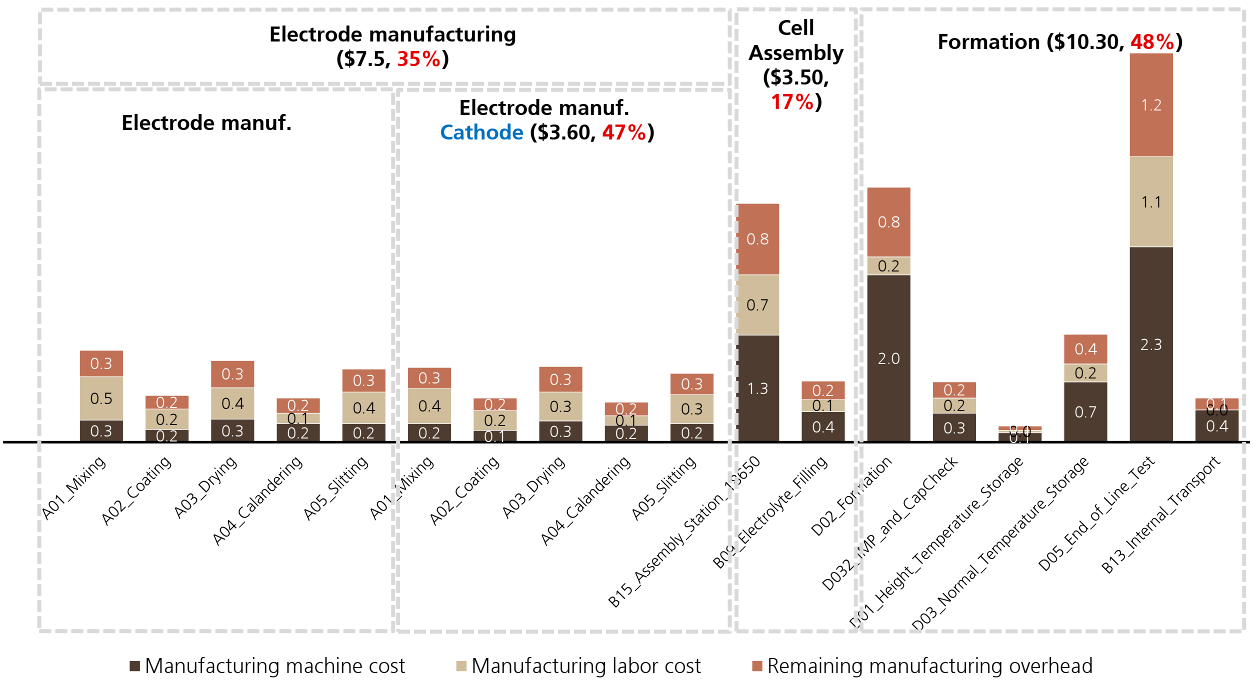
Source: UBS Evidence Lab

Figure 106: Panasonic's 2170 cylindrical cell



Source: UBS Evidence Lab

Figure 107: Manufacturing cost split for Panasonic 4.8 Ah round cell in the US (US$/kWh)



Source: UBS Evidence Lab

2. LG Chem's pouch cell

Advantages: highest gravimetric energy density and cost reduction potential with scale

LG Chem ranks second in energy density (Wh/l) due to its use of a continuous jelly roll. This allows for better space optimization and lower electrolyte use. The lean housing design of LG Chem's pouch cell (only pouch foil with terminals and fixation strips minimizes cost share to 4%, or US$3.10/kWh). In terms of gravimetric energy density (Wh/kg), LG Chem's cell ranks number one due to lightweight housing for the pouch format. Housing only accounts for 2% of total cell weight for LG Chem, versus 23% for Panasonic.

Leading in production quality

LG Chemical also has the lowest share of plastic parts as a percentage of cell weight, at 0.04%. This is an indicator of production and design quality. In terms of production quality, LG Chem also comes out on top with its flat cell structure, with a reduced radius through the application of its patented "Bi-cell folding" process.

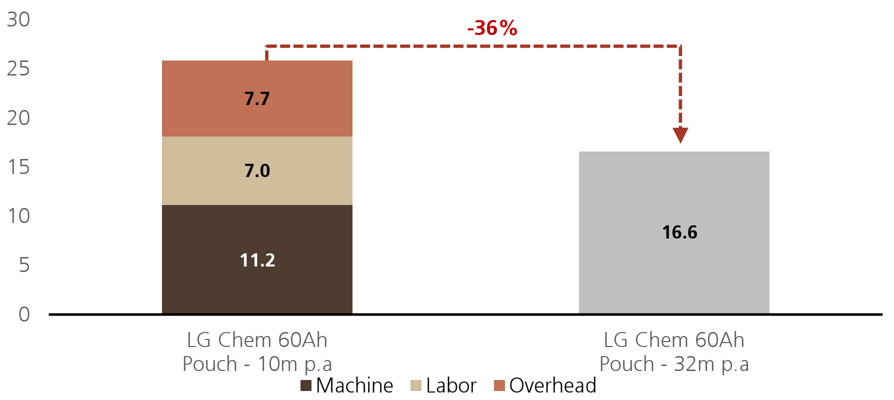
Significant scale for cost reduction

Disadvantages: manufacturing complexity

LG Chem's cell also shows a lot of potential for cost reduction in the manufacturing process. P3 believes the production setup could be optimized, with larger mixer sizes, faster coaters, greater coating widths and significant simplification for end-of-the-line testing potentially leading to cost reductions. P3 estimates that if production volume is also increased from 10m cells p.a. to 32m (7.5GWh), the manufacturing cost per kWh could fall 36%, to US$16.60 per kWh.

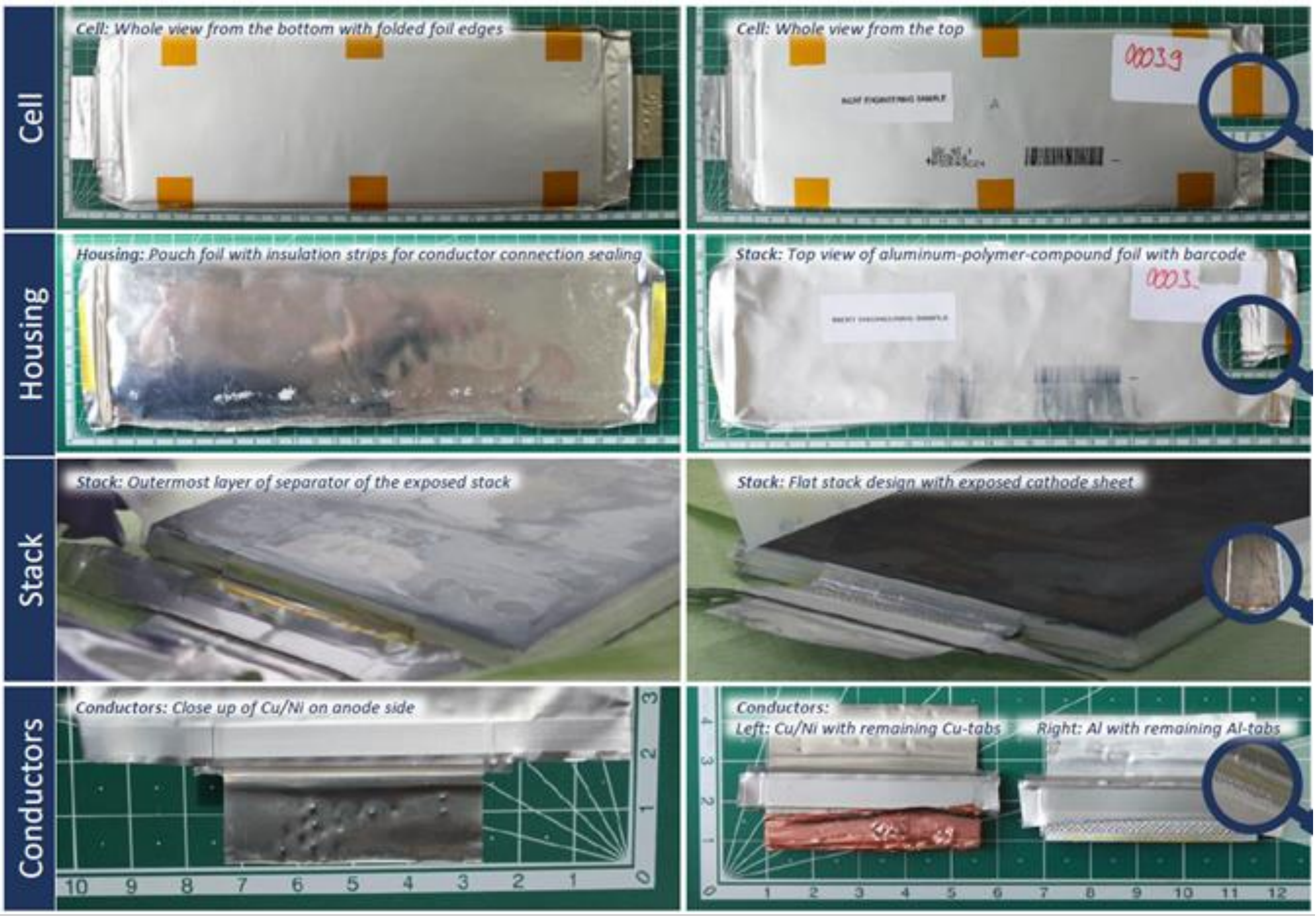
Formation is also a cost driver due the additional degassing phase, accounting for c28% of manufacturing costs, or US$7.30/kWh.

Figure 108: LG's manufacturing cost in US$/kWh



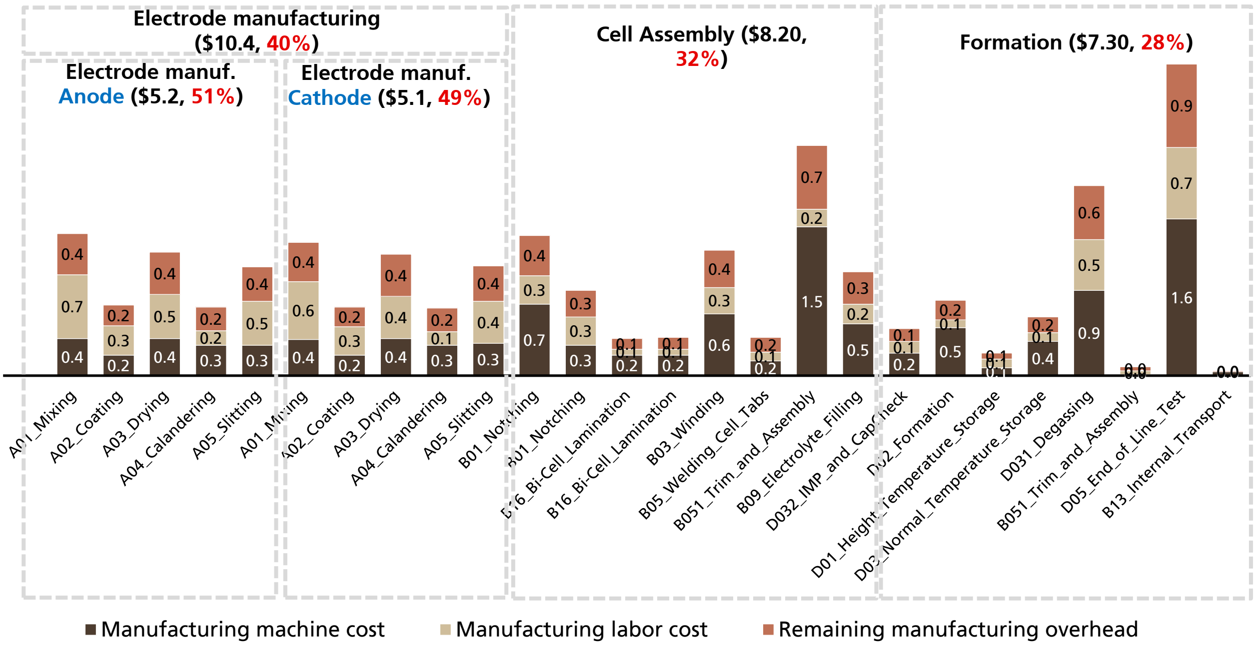
Source: UBS Evidence Lab

Figure 109: LG Chem's NMC 622 pouch cell



Source: UBS Evidence Lab

Figure 110: Manufacturing cost split for LG Chem 60 Ah pouch cell in the US (US$/kWh)



Source: UBS Evidence Lab

3. Samsung SDI's prismatic cells

Samsung SDI's cell includes the most safety features relative to other companies' cells. Specifically, the aluminium can that houses the jelly roll is robust and 20% thicker than the CATL design. Other safety features include a degassing vent, a nail safety device and an overcharge safety device (OSD). Additionally, the SDI uses a multilayer separator that enables cell shut-down.

Samsung SDI's cell has more safety features than other companies' cells

Four separate jelly rolls raise manufacturing costs

Samsung SDI's cell is the largest and heaviest. It includes four jelly rolls versus only two for CATL. The combination of more jelly rolls and a large number of safety features results in SDI having the most complex production process, the highest number of parts and a high manufacturing cost. However, multiple jelly rolls increase flexibility and line utilization. Given the constraints of aluminium can housing, more jelly rolls provide battery volume efficiency. SDI ranks last in terms of energy density (Wh/l)/gravimetric weight (Wh/kg) due to its space-consuming collector set-up, thick can walls, large number of components and excess foil.

Among prismatic cells, SDI uses relatively few plastic parts, at 1.6% of the total. Overall, SDI ranks third in production quality.

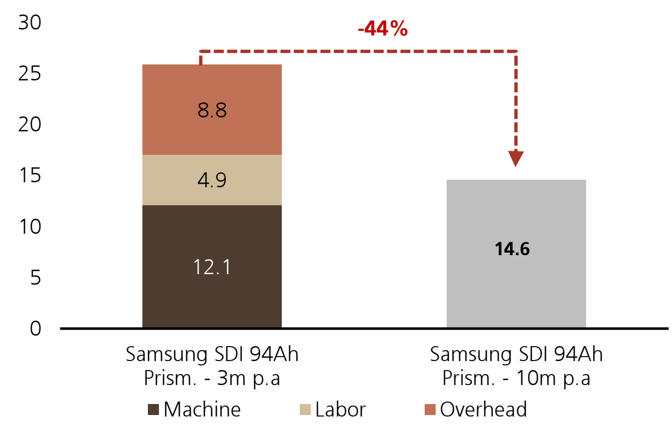
Greatest potential to reduce manufacturing cost

SDI has the greatest potential for lowering manufacturing cost, with an expected 43% reduction in manufacturing costs. This could be achieved through an increase in cell production volume from 3m p.a. to 10m (3.4GWh). Additionally, in the optimized scenario, more sophisticated machinery and higher throughput number were assumed. SDI probably has even more potential to reduce cost by using a thinner can and reducing the number of safety features.

SDI offers an expected 43% reduction in manufacturing costs

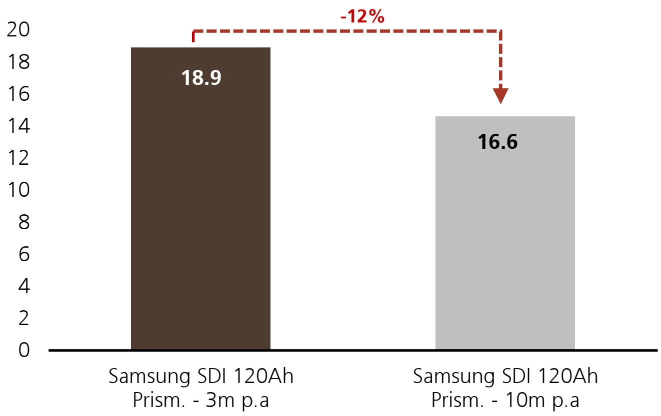
Electrode manufacturing is the major cost driver (58% of total) due to low line utilization. Time-consuming formation and end-of-the-line steps drive costs and lead to a 23% share of total manufacturing cost.

Figure 111: Samsung SDI's manufacturing cost (94 Ah) in USD/kWh



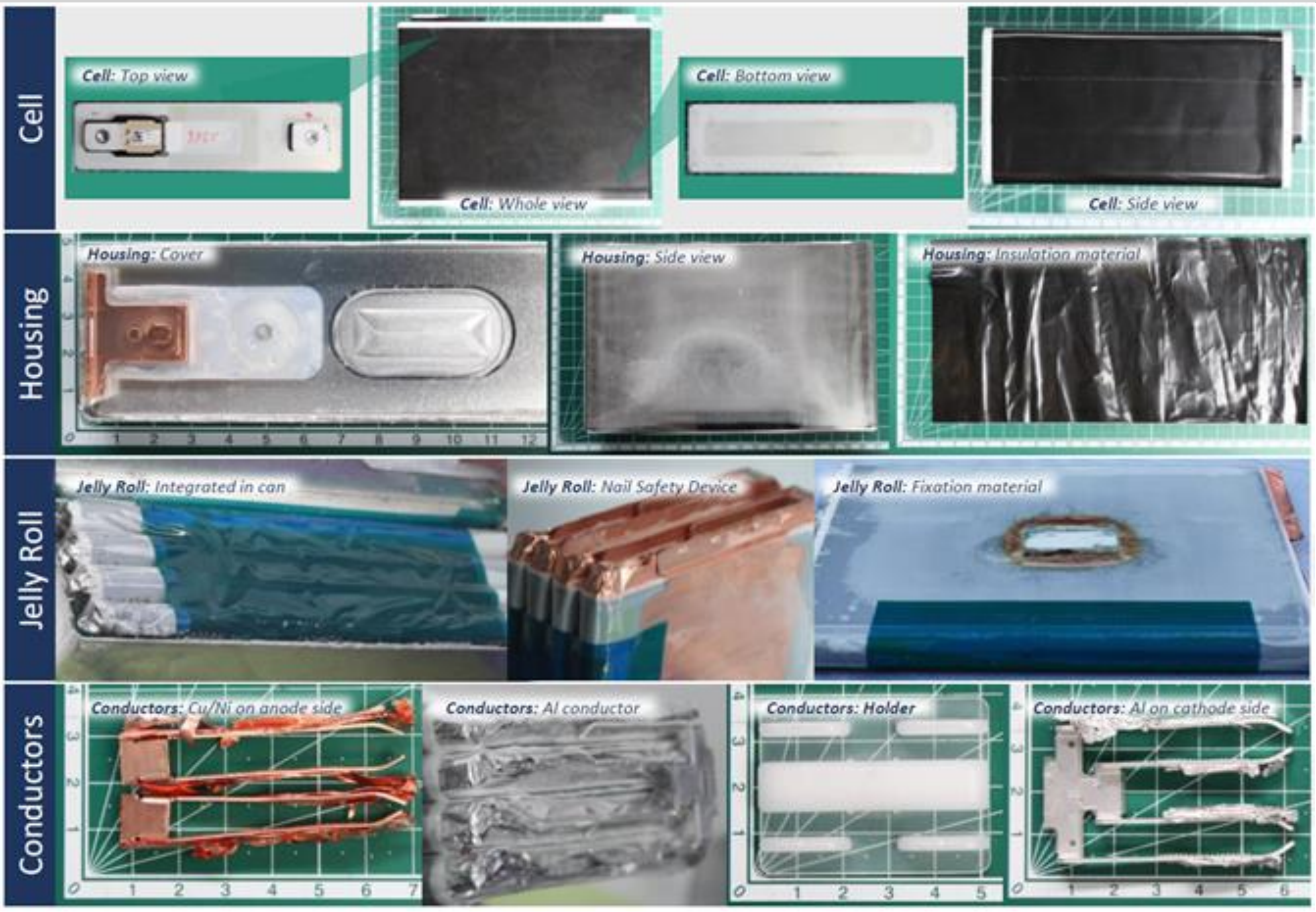
Source: UBS Evidence Lab

Figure 112: Samsung SDI's manufacturing cost (120Ah)



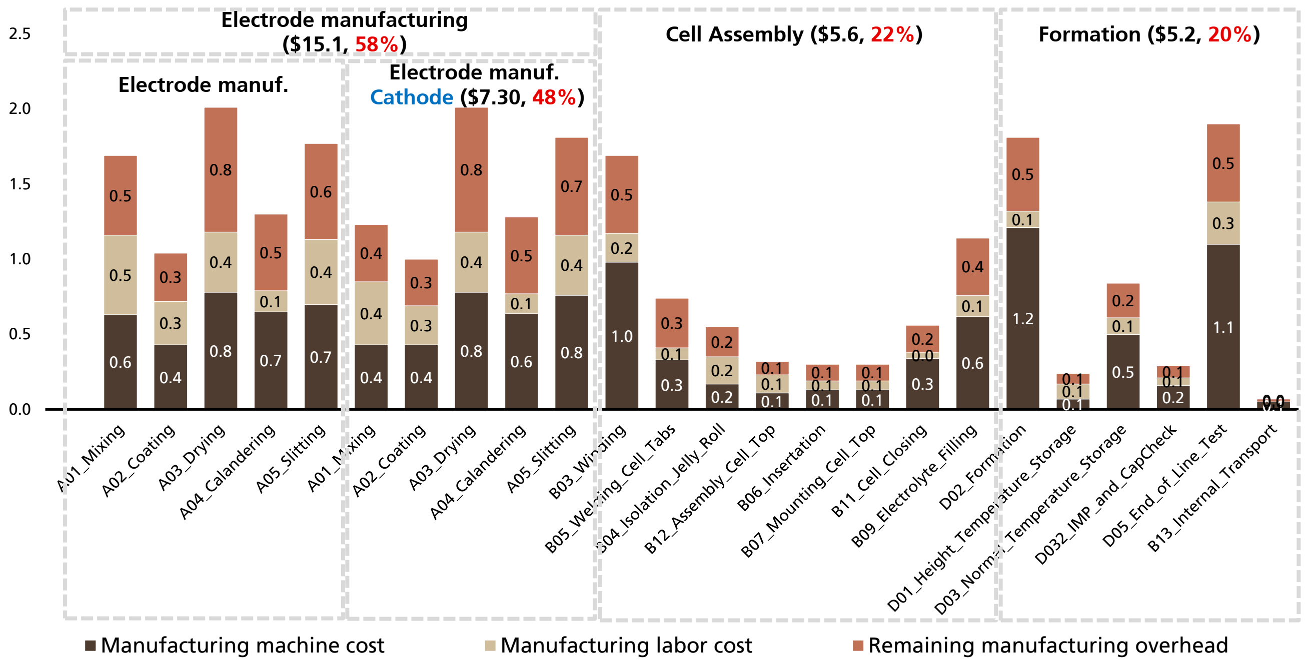
Source: UBS Evidence Lab

Figure 113: Samsung SDI's prismatic NMC 111 cell



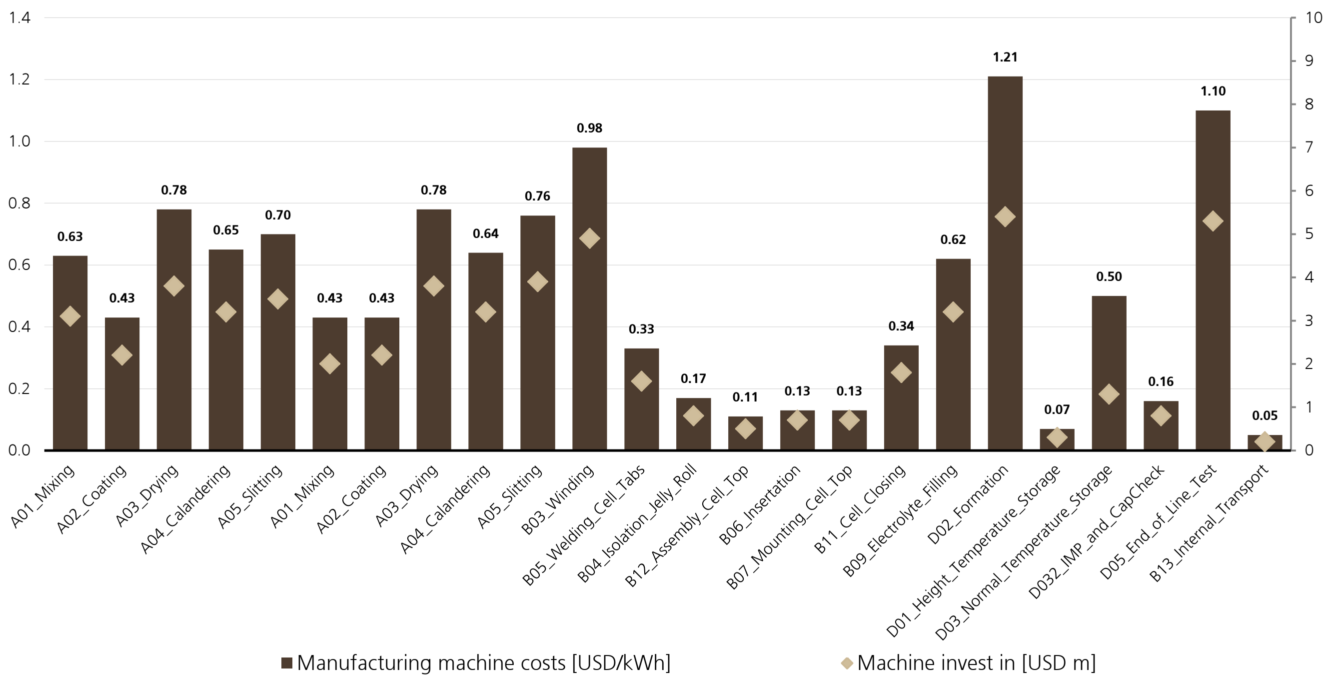
Source: UBS Evidence Lab

Figure 114: Manufacturing cost split for Samsung SDI 94 Ah prismatic cell in South Korea (US$/kWh)



Source: UBS Evidence Lab

Figure 115: Samsung SDI's machine capex



Source: UBS Evidence Lab

4. CATL's prismatic cells

CATL's prismatic cell has fewer safety features than SDI's…

CATL's prismatic cell has fewer safety features than SDI's prismatic cell. CATL's aluminium can is also 20% thinner than SDI's. The CATL cell features two jelly rolls, versus Samsung SDI's four. The two-jelly-roll setup reduces the number of connection points between jelly rolls and reduces inactive space. There is also significant excess material in the CATL cell, including free electrolyte (electrolyte outside the jelly roll) and anode/cathode foils. Despite its excess material, CATL has managed to save costs relative to SDI by reducing the number of components and using less cost-intensive materials. Additionally, CATL uses a high-nickel core shell material cathode that performs slightly below NMC 622, whereas SDI is still using an NMC-111 cathode. Taken together, these factors result in CATL ranking third in terms of energy density (Wh/l) and gravimetric energy (Wh/kg).

Lagging in production quality

…and ranks last when it comes to production quality

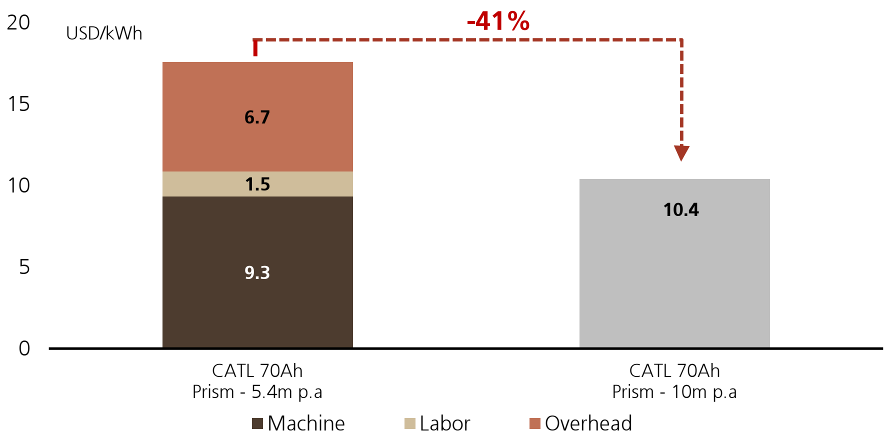
CATL also ranks last in terms of production quality. CATL uses an excess separator to compensate for electrode winding inaccuracies, which lowers space efficiency. CATL also uses the greatest number of plastic parts, and plastic accounts for 2.4% of CATL's cell weight. CATL uses plastic for insulating materials. Plastic materials are also used to fixate and connect the jelly rolls. The high level of plastic usage represents a disadvantage when it comes to the cell's production quality and design.

Meaningful headroom to reduce manufacturing costs

CATL has significant potential for lowering manufacturing cost – P3 estimates a 43% potential reduction. This could be achieved through an increase in cell production volume from 5.4m p.a. to 10m (2.6GWh). Additionally, in the optimized scenario, cycle time reduction was assumed for end-of-the-line testing.

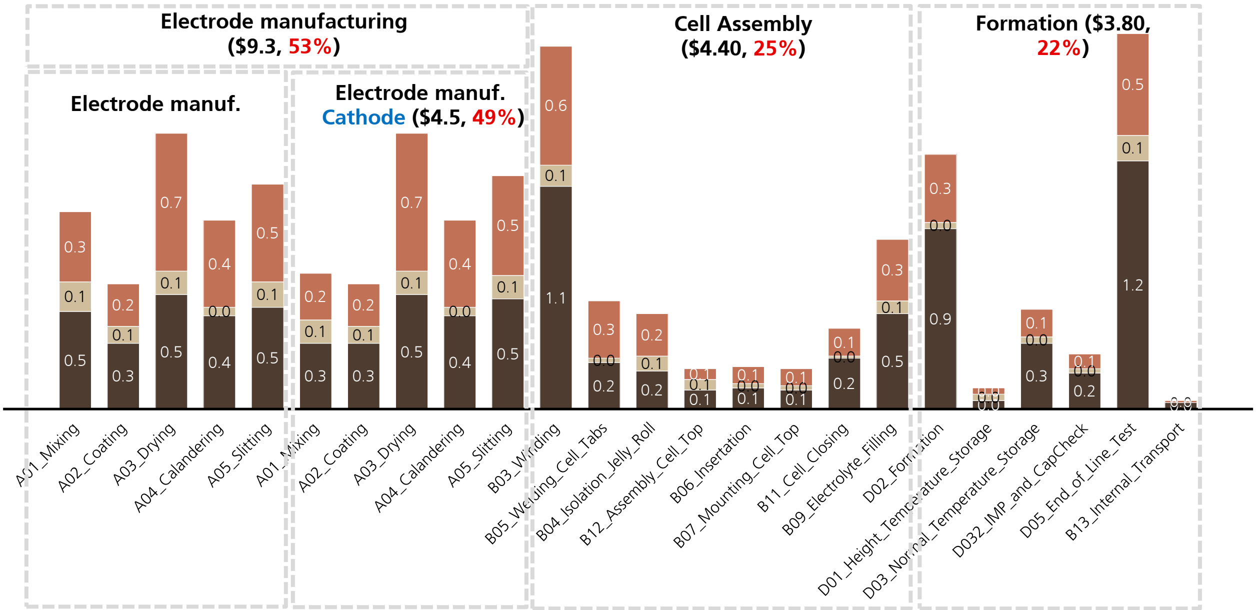
Jelly roll winding is the most cost-intensive step as CATL's jelly rolls are long, which increases cycle time. Time-consuming formation and end-of-the-line steps are the largest process step cost drivers. These two production steps account for 20% of total manufacturing cost. Electrode manufacturing is the major cost driver (53% of total), due to low line utilization.

Figure 116: CATL's manufacturing cost



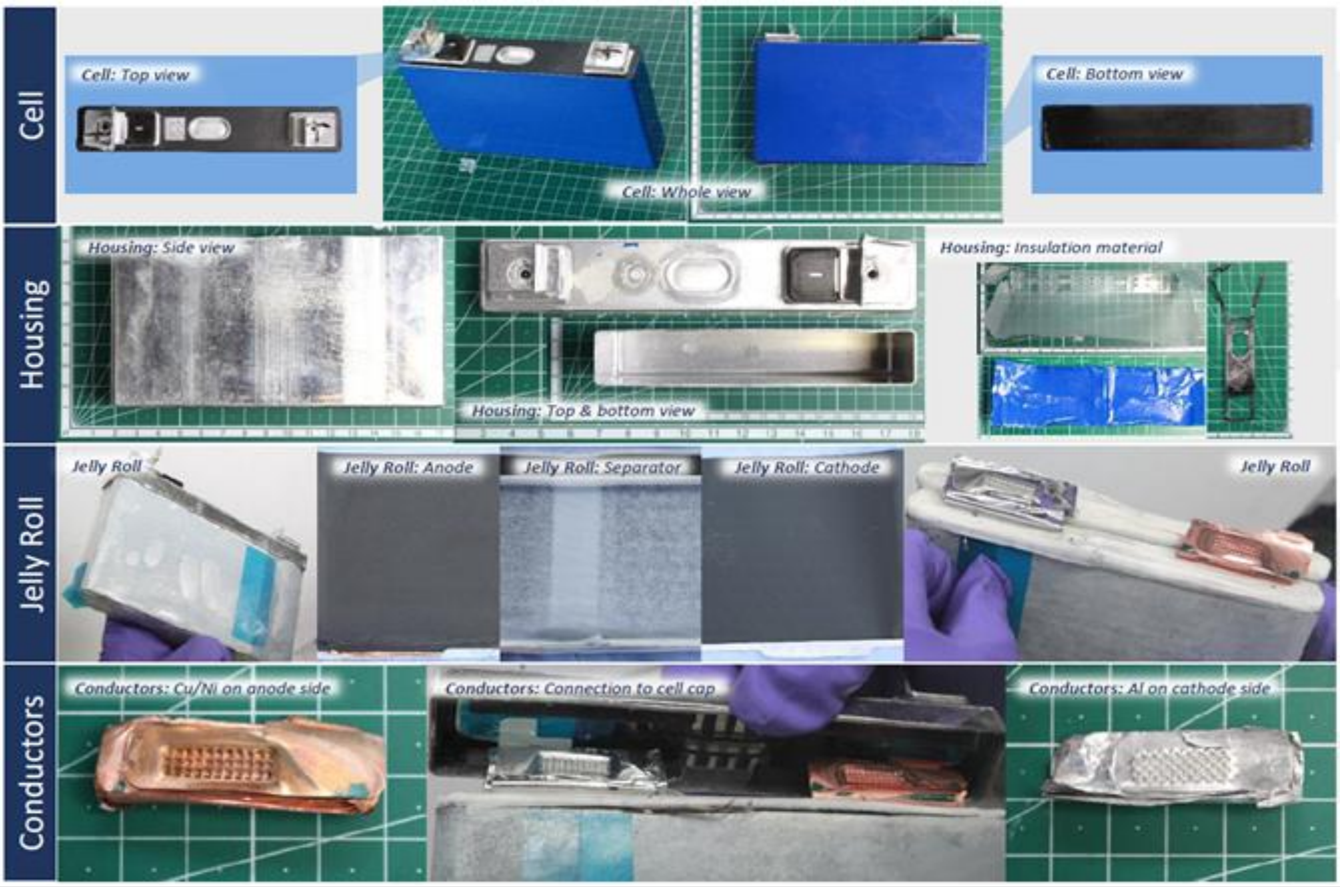
Source: UBS Evidence Lab

Figure 117: Manufacturing cost split for CATL 70 Ah prismatic cell in China (US$/kWh)



Source: UBS Evidence Lab

Figure 118: CATL's prismatic NMC5/2.5/2.5 cell



Source: UBS Evidence Lab

BEV model overview

Figure 119: BEV line-up (ex China)

		Range (EPA)	Price	Battery capacity	Fast charging time	Power	Battery supplier
OEM	**Model name**	**km**	**$**	**kWh**	**mins**	**HP**	
2009							
Daimler	Smart Electric Drive	110	26,070	18	n/a	75	Tesla (Panasonic)
2010							
Mitsubishi	i MiEV	100	23,760	16	~30	67	GS Yuasa
Peugeot	Peugeot iOn	110	19,635	15	~30	67	GS Yuasa
Peugeot	Citroen C-Zero	110	19,635	15	~30	67	GS Yuasa
2011							
Renault	Twizy	100	7,700	6	n/a	17	LG Chem
Renault	Kangoo Z.E.	110	22,330	22	n/a	60	AESC / LG Chem
Renault	Fluence Z.E.	100	28,600	22	n/a	94	AESC / LG Chem
Nissan	Leaf (24kWh)	120	29,040	24	~30	107	AESC
2012							
Tesla	Model S 75D	417	65,200	70 / 100	~30-45	315	Panasonic
Tesla	Model S 100D	540	84,700	90	30-45	373	Panasonic
Ford	Focus Electric	76	29,194	23	n/a	130	LG Chem
Bolloré	Bluecar	200	20,900	30	n/a	68	-
Honda	Fit EV	135	35,970	20	n/a	75	GS Yuasa
2013							
Renault	Zoe	170	23,650	22	~30	88	LG Chem
BMW	i3	135	38,500	19	~30	170	Samsung SDI
Volkswagen	VW e-Up!	120	29,700	19	~30	82	Toshiba
FCA	Fiat 500e	140	32,010	24	n/a	111	Samsung SDI / Bosch
GM	Chevy Spark EV	135	25,960	19	~30	140	LG Chem
2014							
Volkswagen	VW e-Golf	135	38,500	24.20	~30	115	Panasonic
Daimler	Mercedes B-Class ED	140	43,120	28	n/a	179	Tesla (Panasonic)
Kia	Soul EV	160	30,800	27	~30	109	SK Innovation
Nissan	e-NV200	170	26,400	24	30	109	AESC
2015							
Tesla	Model X – 75D	382	71,300	75	~30-45	328	Panasonic
Tesla	Model X – 100D	475	87,800	100	~30-45	525	Panasonic
Nissan	Leaf (24kWh – upgr.)	135	29,040	24	~30	107	AESC
Nissan	Leaf (30kWh)	170	33,990	30	~30	107	AESC
2016							
BMW	i3 (upgrade)	185	42,200	30	~30	170	Samsung SDI
Peugeot	Citroen e-Mehari	100	30,580	30	~30	48	Bolloré
GM	Chevy Bolt	385	37,400	60	~60	200	LG Chem
Daimler	Smart Fortwo	110	24,200	18	~30-45	81	LG Chem
Renault	Zoe (upgrade)	300	35,200	41	~60	91	LG Chem
2017							
Hyundai	Ioniq EV	200	36,300	28	~30	118	LG Chem
Volkswagen	VW e-Golf (upgrade)	200	39,490	36	~30	135	Samsung SDI
Daimler	Smart Forfour	110	24,860	18	~30-45	81	LG Chem
Daimler	Smart Cabrio	110	27,720	18	~30-45	81	LG Chem
Honda	Clarity EV	145	59,000	26	~30	161	-

Source: Manufacturer data, EPA, Media reports, UBS

Figure 120: BEV line-up (ex China) – continued

OEM	Model name	Range (EPA) km	Price $	Battery capacity kWh	Fast charging time mins	Power HP	Battery supplier
2017							
Tesla	Model 3 (55kWh)	355	35,000	53	~30	257/346	Panasonic
Tesla	Model 3 (75kWh)	500	44,000	75	~30	257/346	Panasonic
Nissan	Leaf (40kWh)	243	29,990	40	~40	150	AESC
BMW	i3s (sport version)	200	45,300	30	~30	184	Samsung SDI
2018							
Hyundai	Kona EV (39kWh)	300	38,000	39	~30	135	LG Chem
Hyundai	Kona EV (64kWh)	470	45,000	64	~40	204	LG Chem
Kia	Niro EV	385	<40,000	64	~45-60	204	SK Innovation
JLR	Jaguar I-Pace	377	69,500	90	~45	400	LG Chem
Volkswagen	Audi e-tron	400-450	74,800	95	~30	335	LG Chem/Sam. SDI
2019							
Nissan	Leaf (longer-range)	360	-	60	-	160	LG Chem
Volkswagen	VW I.D.	330	>27,000	48	~30	170	LG Chem
Volkswagen	VW I.D.	450	-	-	-	-	LG Chem
Volkswagen	VW I.D.	550	-	75	-	-	LG Chem
Volkswagen	Audi e-tron Sportback	500	-	-	~30	-	LG Chem/Sam. SDI
Volkswagen	Porsche Taycan	500	90,000	90-100	~15	600	-
Daimler	EQC	360	65,000	80	~40-45	400	SK Innovation
Volvo	CX40 BEV	500	50,000	-	-	-	-
BMW	e-Mini	-	-	-		-	-
BMW	i3 (upgrade)	246	-	42	-	171/ 181	-
PSA	DS 3 E-Tense	300	-	50	~30	136	-
PSA	Peugeot 208 BEV	-	-	-	-	-	-
PSA	Opel Corsa BEV	-	-	-	-	-	-
Honda	Compact 'Urban' BEV	250	-	-	-	-	-
GM	2 BEVs based on Bolt	-	-	-	-	-	-
2020							
Daimler	EQA	400+	-	-	-	270	-
Daimler	EQS	-	-	-	-	-	-
Daimler	All Smart models electric	-	-	-	-	-	-
BMW	iX3	400+	65,000	>70	-	270	CATL
Volkswagen	Audi e-tron GT	-	-	-	-	-	-
Volkswagen	VW I.D. Crozz	400-600	35,000	83	-	300	-
Volkswagen	Skoda Vision E	-	-	-	-	-	-
Volkswagen	Seat Mii	-	-	-	-	-	-
PSA	Peugeot 2008 BEV	-	-	-	-	-	-
Ford	"Mach 1" BEV	-	-	-	-	-	-
Honda	3rd BEV model	-	-	-	-	-	-
Hyundai	2 new BEVs	-	-	-	-	-	-
Kia	2 new BEVs	-	-	-	-	-	-
Tesla	2nd gen Roadster	1,000	200,000+	200	-	-	Panasonic
Tesla	Model Y	-	-	-	-	-	Panasonic
Mazda	BEV	-	-	-	-	-	-
Mitsubishi	BEV	-	-	-	-	-	-

Source: Manufacturer data, EPA, Media reports, UBS

Figure 121: BEV line-up (ex China) – continued

OEM	Model name	Range (EPA) km	Price $	Battery capacity kWh	Fast charging time mins	Power HP	Battery supplier
2021+							
BMW	i-Next (2021)	500+	-	-	-	-	Samsung SDI and/or CATL
BMW	i4	-	-	-	-	-	Samsung SDI and/or CATL
Volkswagen	2nd Porsche BEV (2021)	-	-	-	-	-	-
Volkswagen	VW I.D. Buzz (2021)	-	-	-	-	-	-
Volkswagen	VW I.D. Vizzion (2021)	-	-	-	-	-	-
PSA	4 BEVs by 2021	-	-	-	-	-	-
Volvo	CX90 BEV (2021)	-	-	-	-	-	-
Volvo	2 more BEVs by 2021	-	-	-	-	-	-
Volvo	2 Polestar BEVs by 2021	-	-	-	-	-	-
Hyundai	Genesis BEV (2021)	-	-	-	-	-	-
Daimler	10 EQ BEVs by 2022	-	-	-	-	-	-
Renault/Nissan	12 BEVs by 2022	-	-	-	-	-	-
Ford	16 BEVs by 2022	-	-	-	-	-	-
GM	20 BEVs by 2023	-	-	-	-	-	-
Volkswagen	12 Audi BEVs by 2025	-	-	-	-	-	-
Volkswagen	5 Skoda BEVs by 2025	-	-	-	-	-	-
Volkswagen	Group: 50 BEVs by 2025	-	-	-	-	-	-
Toyota	10 BEVs by 2025	-	-	-	-	-	-

Source: Manufacturer data, EPA, Media reports, UBS

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For this report, UBS Evidence Lab entered a partnership with P3, an engineering consultancy with a dedicated practise area in batteries for electric cars. On behalf of UBS Evidence Lab, P3 performed a teardown of the leading EV battery cells from Panasonic, LG Chem, Samsung SDI and CATL, including a detailed analysis of chemicals/materials used, manufacturing processes, battery performance and cost.

The cost estimates reflect all direct costs such as raw materials, labour, depreciation and a 5% profit margin for the producer. P3 did not include general R&D and warranty provisions, which UBS Research added to the P3 estimates.

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Neutral	FSR is between -6% and 6% of the MRA.	37%	21%
Sell	FSR is > 6% below the MRA.	15%	12%
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Buy	Stock price expected to rise within three months from the time the rating was assigned because of a specific catalyst or event.	<1%	<1%
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Source: UBS. Rating allocations are as of 30 September 2018.
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Albemarle Corp[16]	ALB.N	Buy	N/A	US$100.98	16 Nov 2018
Asahi Kasei	3407.T	Buy	N/A	¥1,215.0	19 Nov 2018
BASF SE[7, 14]	BASFn.DE	Neutral	N/A	€69.37	16 Nov 2018
BMW[7]	BMWG.DE	Neutral	N/A	€73.74	16 Nov 2018
Clariant[3a, 3b, 4, 5, 6b, 6c, 7]	CLN.S	Neutral	N/A	CHF21.25	16 Nov 2018
Contemporary Amperex Technology	300750.SZ	Not Rated	N/A	Rmb79.35	19 Nov 2018
Daimler[7]	DAIGn.DE	Neutral	N/A	€50.49	16 Nov 2018
Ems-Chemie[5]	EMSN.S	Sell	N/A	CHF549.00	16 Nov 2018
Faurecia[13]	EPED.PA	Neutral	N/A	€39.99	16 Nov 2018
FCA[3c, 7, 16]	FCHA.MI	Buy	N/A	€14.36	16 Nov 2018
Ford Motor Co.[4, 6a, 7, 16]	F.N	Buy	N/A	US$9.05	16 Nov 2018
Garrett Motion Inc[5, 13, 16]	GTX.N	Sell	N/A	US$12.05	16 Nov 2018
General Motors Company[6b, 7, 16]	GM.N	Buy	N/A	US$35.75	16 Nov 2018
Guoxuan High-Tech	002074.SZ	Sell	N/A	Rmb12.81	19 Nov 2018
Hyundai Motor	005380.KS	Buy	N/A	Won101,500	19 Nov 2018
Johnson Matthey	JMAT.L	Sell	N/A	3,000p	16 Nov 2018
LG Chemical	051910.KS	Buy	N/A	Won345,500	19 Nov 2018
Nissan Motor	7201.T	Sell	N/A	¥1,005.5	19 Nov 2018
Panasonic[7]	6752.T	Neutral	N/A	¥1,115.0	19 Nov 2018
PSA Group[1, 5]	PEUP.PA	Neutral	N/A	€19.82	16 Nov 2018
Renault[7, 13]	RENA.PA	Neutral	N/A	€64.50	16 Nov 2018
SAIC Motor	600104.SS	Buy	N/A	Rmb25.75	19 Nov 2018
Samsung SDI	006400.KS	Buy	N/A	Won222,500	19 Nov 2018
Schaeffler[13]	SHA_p.DE	Sell (UR)	N/A	€7.76	16 Nov 2018
SK Innovation	096770.KS	Buy	N/A	Won203,000	19 Nov 2018
Tesla, Inc.[16, 22]	TSLA.O	Sell	N/A	US$354.31	16 Nov 2018
Toyota Motor[7, 16]	7203.T	Neutral	N/A	¥6,612	19 Nov 2018
Umicore	UMI.BR	Neutral	N/A	€41.50	16 Nov 2018
Victrex Plc[13]	VCTX.L	Buy	N/A	2,680p	16 Nov 2018
Volkswagen[7, 13]	VOWG_p.DE	Buy	N/A	€143.92	16 Nov 2018
W. R. Grace & Co[16]	GRA.N	Buy	N/A	US$63.85	16 Nov 2018

Source: UBS. All prices as of local market close.
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