Note: The following is a redacted version of the original report published 1 June, 2022 [37 pgs].

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Batteries: The Greenflation Challenge II: Raising battery price forecasts; addressing six key investor debates

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We raise our global average battery pack price forecasts over 2022E/23E/24E/25E by 18%/26%/15%/8% (rising from US$133/kWh in 2021 to US$164/kWh in 2023E before falling towards US$114/kWh in 2025), reflecting our Commodities team's latest forecasts for battery metals. While the battery metals bull market appears to have peaked, our new metals forecasts are still higher than our prior assumptions in battery cost curve, leading to revision up in battery price forecasts. The shape of the battery cost path is largely unchanged – ie we continue to see a hiccup in battery cost deflation over 2022/23 but battery innovations and more efficient manufacturing should continue to drive a long-term price decline. Our Autos team also lowers its global car sales forecasts by 3-5% but keeps the EV penetration mix largely unchanged. Overall the greenflation challenge is looking more manageable to us with battery metals cost (especially Lithium) peaking out, battery makers (ex-China) appear to be passing through most of cost inflation to OEMs with our updated model suggesting ex-China battery supply demand could remain tight through 2025, and EV penetration rates are still rising despite higher battery prices given higher fuel savings from elevated oil prices. In this note we address six key debates which we view as top of mind for investors:

1. How much of battery chemistry improvement is offset by greenflation? With our new battery metal price forecasts still broadly higher than historical 5-year average levels, we calculate overall higher commodity prices offset ~40% of the cost deflation contributed by technology and chemistry improvement over 2020-25.

2. How would higher battery prices impact EV penetration? More fuel savings from higher oil prices implies cost parity of EVs to ICE in a broader part of the industry could still be achieved by 2025. Longer term, we believe sustainable EV supply growth would require a more diversified battery chemistry mix and recycling of metals from retired batteries.

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3. How are new innovations progressing in solid state batteries? Our tracking suggests many companies are now working on solid state batteries, testing diversified technology routes. Still, multiple challenges exist (eg. scaling up cell layers) and mass production looks less likely before the late 2020s.

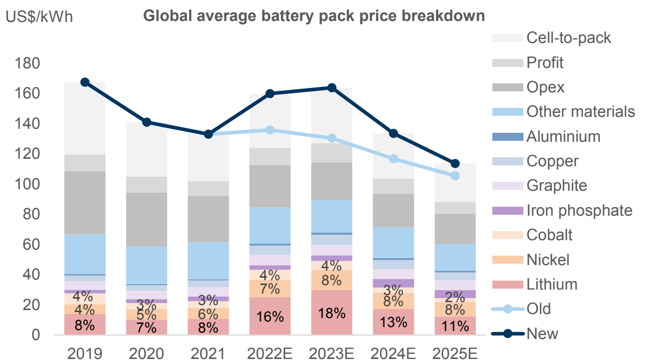
4. Will supply chain complexity impact new startups and will the battery industry remain consolidated? Battery supply chain complexity is becoming another barrier for new entrants (in addition to incumbent top players' technology leadership) suggesting the battery industry will likely remain consolidated this decade.

5. Has bargaining power shifted from OEMs to battery makers? The balance of power appears to be shifting from OEMs to battery makers, especially in the ex-China market where battery supply demand is tight, the battery industry is more consolidated and increasingly most battery materials cost is becoming a pass-through in contracts with OEMs.

6. How do we see the competitive positioning and valuation risk-reward of battery companies? Both LGES and CATL are leading the technology debate, but we note LGES winning more customer mix in tighter battery supply demand regions while CATL remains the cost curve leader.

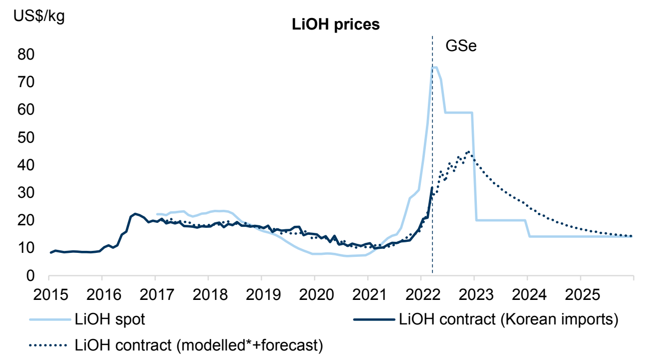
Thesis in 12 key charts

Exhibit 1: The cost of lithium and nickel account for 10-20% and c.10%, respectively, of global average battery pack prices (during 2022-25E)...



Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

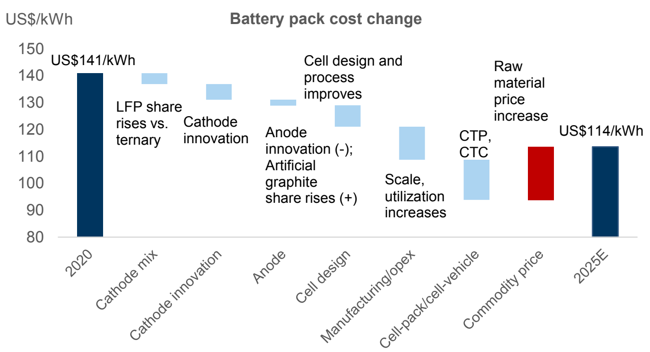
Exhibit 2: ...while the battery metals bull market has peaked, we believe contract lithium hydroxide prices will likely peak in 4Q22



*Modelled LiOH contract prices using a 2-month lag on earlier contract prices and no lag on spot prices

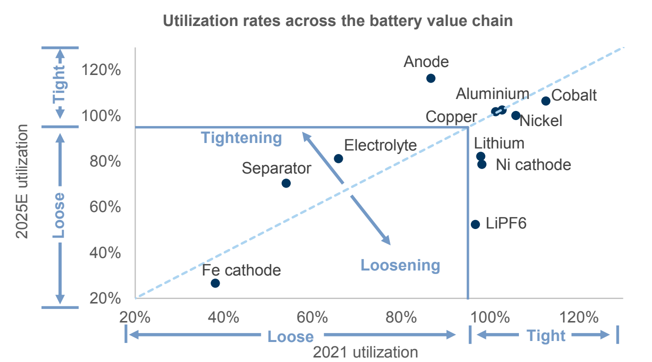
Source: Refinitiv, KITA, Goldman Sachs Global Investment Research

Exhibit 3: We raise our battery pack price forecasts on our Commodities team's higher commodity prices outlook



Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

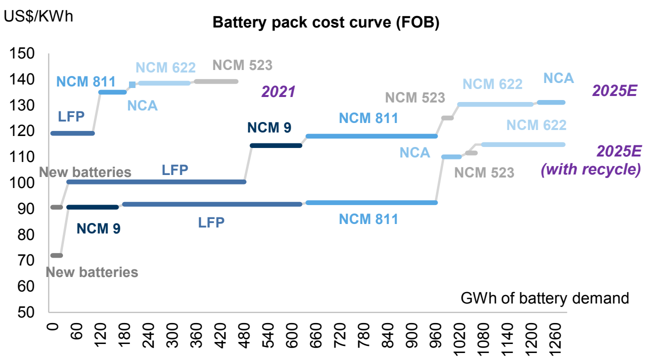
Exhibit 4: Along the battery value chain, supply is running tight in anodes, select base metals, and nickel cathodes



Demand / supply for raw materials; demand / capacity for processed materials and components; limited by forecast period, nickel and aluminium using 2023E for 2025E

Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

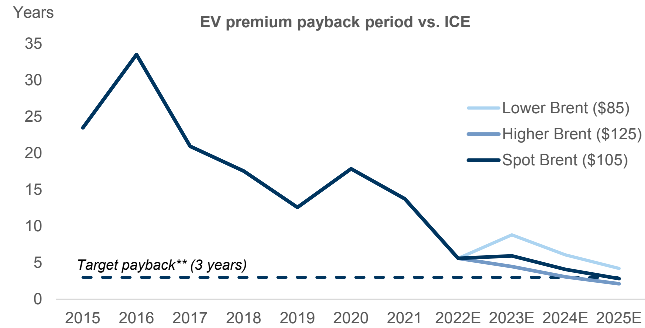
Exhibit 5: Battery technology development and recycling will flatten the 2025 cost curve between NCM vs LFP



NCM refers to Nickel Cobalt and Manganese chemistry; LFP refers to Lithium Iron Phosphate chemistry

Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

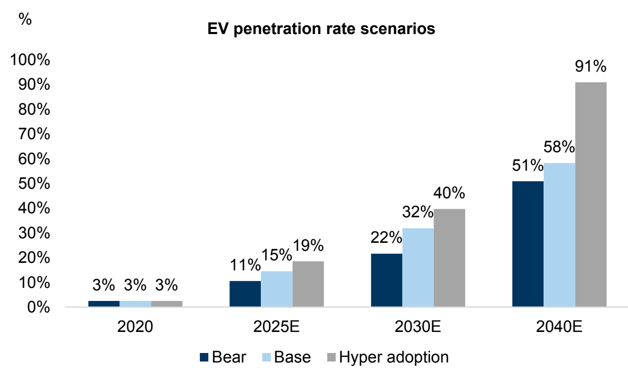
Exhibit 6: Even if battery prices rise more than previous expectations, the oil strength will likely support EV sales



*Toyota Prius achieved a breakthrough in sales after shortening the payback period to 3 years

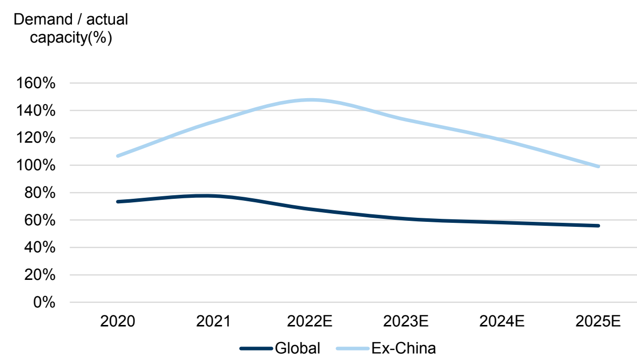
Source: Goldman Sachs Global Investment Research

Exhibit 7: We keep our EV penetration rates largely unchanged despite the cut to global automobile sales in 2022, 2023



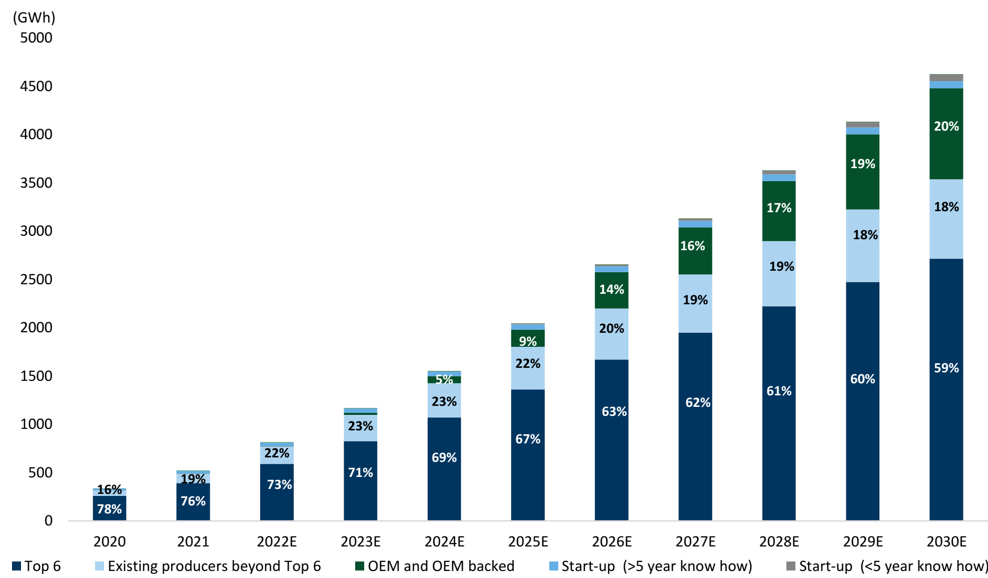
Source: Goldman Sachs Global Investment Research

Exhibit 8: Global battery supply/demand is expected to loosen going forward, while the ex-China market will likely remain tight...
Battery supply demand (Global, ex-China)



Source: Goldman Sachs Global Investment Research

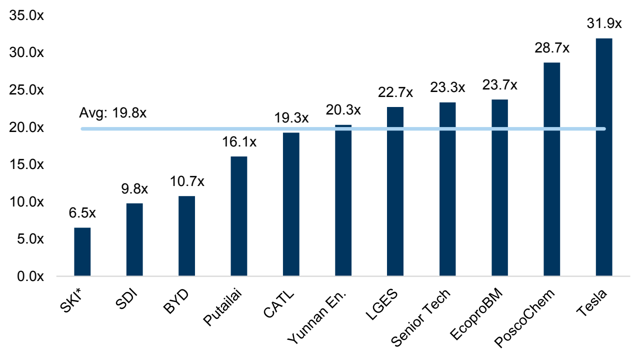
Exhibit 9: ...with the top 6 players still dominating the cell manufacturing market through 2030



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 11: Overall valuation within the EV battery valuechain has declined from higher interest rates and headwinds from higher metal prices...

2023E EV/EBITDA multiple of EV value chain

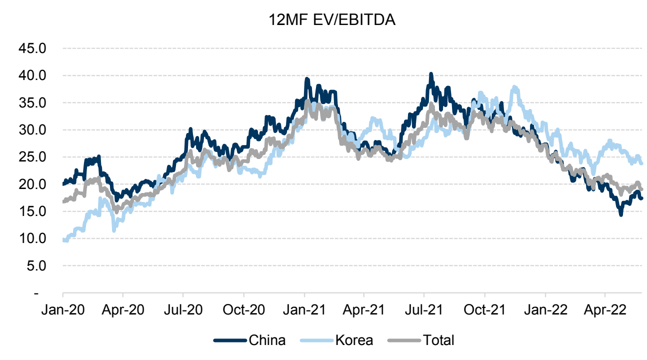


*SKI: Based on implied EV battery business only / estimates for Not Covered Ecopro BM & Posco Chem from Bloomberg, others from GSe

Source: Bloomberg, Goldman Sachs Global Investment Research

Exhibit 12: ...and the Korean battery valuechain is now trading at a premium to China

12MF EV/EBITDA by country within the EV battery valuechain



China: CATL, BYD, EVE Energy, Ningbo Shanshan, Shanshan, Yunnan Energy, Putailai, Senior Tech, Tinci Materials, Capchem, Korea: LGES, Samsung SDI, EcoproBM, L&F, SKIET, Enchem

Source: Bloomberg

#1: How much of battery chemistry improvement is offset by greenflation?

Higher commodity prices will offset ~40% of the cost deflation contributed by technology and chemistry improvement over 2020-25, on our estimates. While the battery metals bull market appears to have peaked, our new metal price forecasts are still higher than historical 5-year average levels (especially for Nickel). Further, spot and contract lithium prices have diverged meaningfully in recent months, especially for the lithium hydroxide market which is dominated by contract-pricing, and we expect contract prices to lag spot prices by 2-3 quarters. Overall we raise our 2022E-25E global average battery pack price forecasts by 8-26% and expect the battery price to peak in 2023.

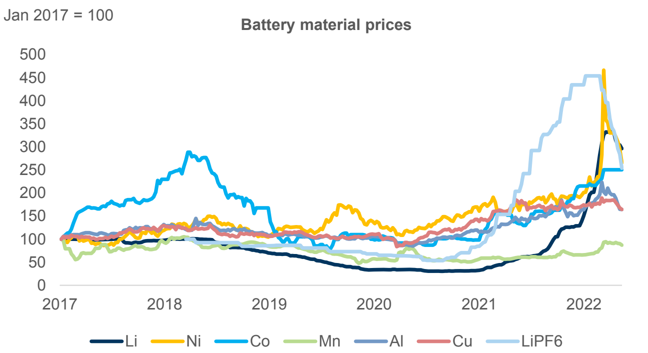
The battery metals bull market appears to have peaked, but the level of metal prices also matters. Battery raw material prices have seen some correction but remain at high levels (Exhibit 14). Our global Commodities team recently introduced new lithium carbonate (spot) forecasts of 61/18.5 ($/kg) in 2022/23E. They reflect a strong lithium price in 2022, while we expect the lithium market to pivot towards a prolonged phase of surplus post a significant tightening trend last year. Lithium hydroxide (contract) prices, on the other hand, will likely show a less steep price increase in 2022 (US$35/kg) but a more sustained level in 2023 (US$32/kg) as well from the longer duration of the contract. For nickel, our Commodities team expects the extreme tightness in the battery grade nickel market to sustain this year, and upgraded its 12m price forecast to US$37,500/t (prior: US$25,000/t). While the team does not believe nickel can sustain prices at such high levels in the long run, the persistent tightness in the forward balances and a lack of class 1 supply in the pipeline lead the team to see prices at elevated levels through the next 2-3 years (2023E US$37,500/t vs. prior US$25,000/t).

Exhibit 13: Key metal and component price changes for global average battery pack prices

Key metal and component price changes														
			Old				New				Change vs. prior			
		2021	2022E	2023E	2024E	2025E	2022E	2023E	2024E	2025E	2022E	2023E	2024E	2025E
LiOH (contract)	US$/kg	12.2	16.0	17.0	17.0	17.0	35.3	32.3	20.2	15.3	121%	90%	19%	-10%
Li_2CO_3 (spot)	US$/kg	18.8	/	/	/	/	61.0	18.5	12.4	12.4	/	/	/	/
Nickel	US$/t	18,499	22,000	25,000	22,377	22,233	31,000	30,250	27,500	27,500	41%	21%	23%	24%
Cobalt	US$/t	51,517	54,950	37,987	33,290	42,549	78,500	59,500	48,000	48,000	43%	57%	44%	13%
Manganese	US$/t	650	676	716	716	716	812	739	761	777	20%	3%	6%	8%
Aluminium	US$/t	2,487	3,450	3,850	2,794	2,586	3,450	3,850	2,829	2,740	0%	0%	1%	6%
Copper	US$/t	9,295	11,875	12,000	9,397	9,172	11,875	12,000	9,405	9,350	0%	0%	0%	2%
Iron phosphate	US$/t	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	2,500	0%	0%	0%	0%
Graphite	US$/t	7,671	8,054	7,410	7,410	6,891	8,438	7,594	7,442	7,219	5%	2%	0%	5%
Silicon	US$/t	15,753	15,753	15,753	15,753	15,753	15,753	15,753	15,753	15,753	0%	0%	0%	0%
Separator	US$/sqm	0.19	0.19	0.18	0.17	0.16	0.19	0.18	0.17	0.16	0%	0%	0%	0%
Electrolyte	US$/t	12,419	12,419	9,935	7,948	6,359	12,419	9,935	7,948	6,359	0%	0%	0%	0%

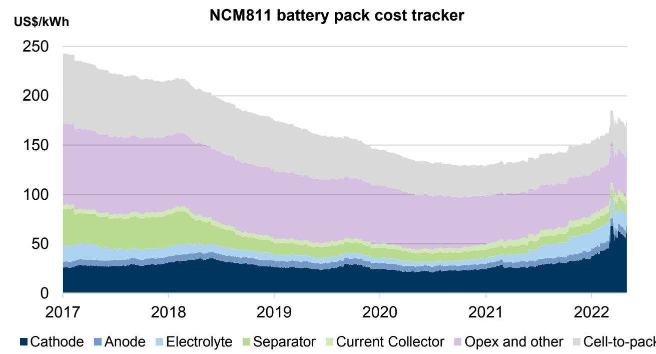
Source: Refinitiv, Wind, Wood Mackenzie, Goldman Sachs Global Investment Research

Exhibit 14: Battery raw material prices have seen some correction, but remain at high levels



Source: Refinitiv, Wind, Goldman Sachs Global Investment Research

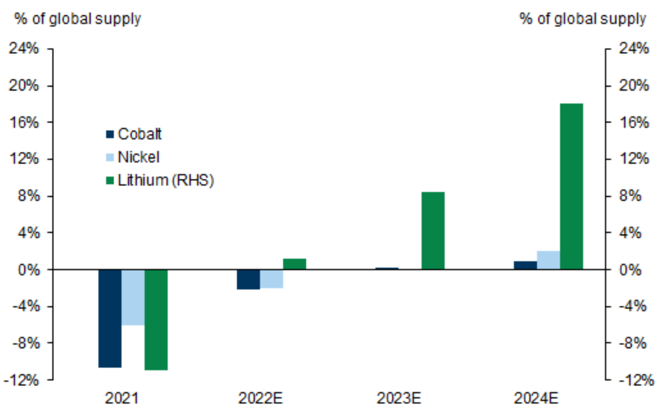
Exhibit 15: …but are still high enough, implying a reversal of over 3 years of chemistry improvement driven battery price reduction



Source: Refinitiv, Wind, Wood Mackenzie, Goldman Sachs Global Investment Research

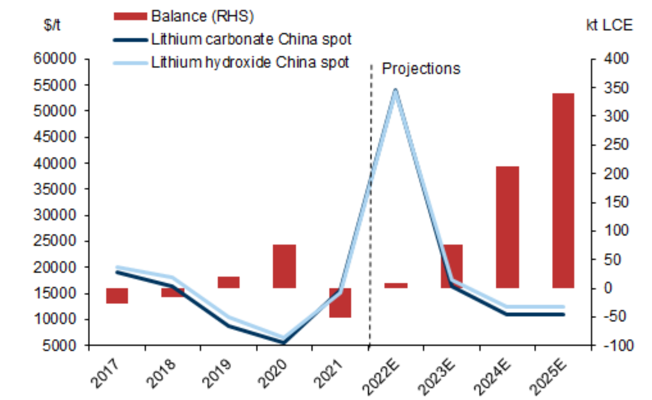
Exhibit 16: A phase of softening fundamentals begins across the battery metals complex

Battery metals balances (% of supply), GSe



Source: Goldman Sachs Global Investment Research

Exhibit 17: We expect a sharp correction in Lithium fundamentals with carbonate and hydroxide prices to fall 70% y/y and 67% y/y, respectively in 2023

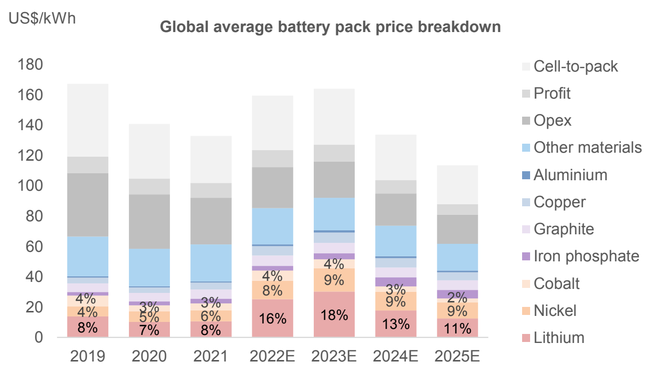


Lithium carbonate China spot: Fastmakets Li carbonate 99.5% Li2CO3 min, China excl. VAT ($/t); Lithium hydroxide China spot: Li hydroxide 56.5% excl. VAT ($/t)

Source: Woodmac, BNEF, Fastmarkets, Bloomberg, Goldman Sachs Global Investment Research

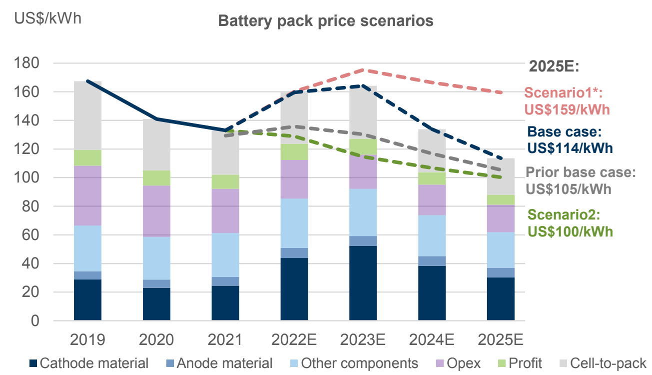
Raising our global average battery pack price forecasts by 8-26% for 2022-25E. The cost of lithium and nickel account for c.10~20% and c.10% of global average battery pack prices, respectively (Exhibit 18). In this calculation, we consider the global weighted average of different types of batteries, inclusive of NCM, LFP, NCA, etc. Following our Commodities team's forecast revisions, we raise our global average battery pack price outlook to US$160/164/kWh for 2022/23E and US$114/kWh by 2025E (prior: US$136/130/kWh for 2022/23E and US$105/kWh by 2025E). We assess that the rising commodity prices offset c.40% of the cost deflation contributed by technology and chemistry improvement over 2020-25 (Exhibit 21).

Exhibit 18: The cost of lithium and nickel account for 10-20% and c.10%, respecitvely, of global average battery pack prices



Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

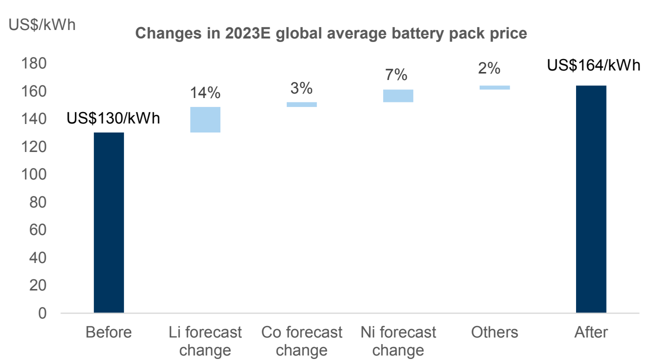
Exhibit 19: We revise up our global average battery pack price forecasts for 2022-25E …



Material price scenarios: 1) 2022 ytd for 2022-25; 2) past 5-year average

Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

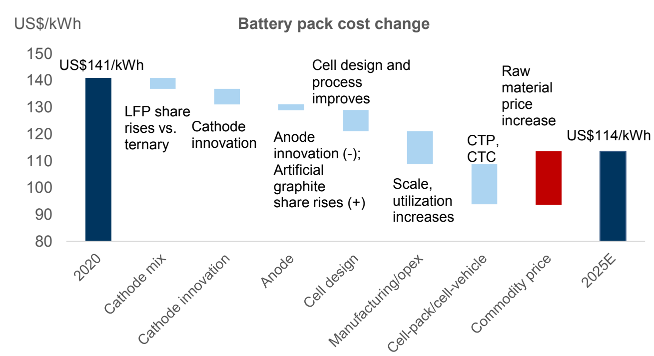
Exhibit 20: ... on a higher commodities price outlook



Li: Lithium, Co: Cobalt, Ni: Nickel

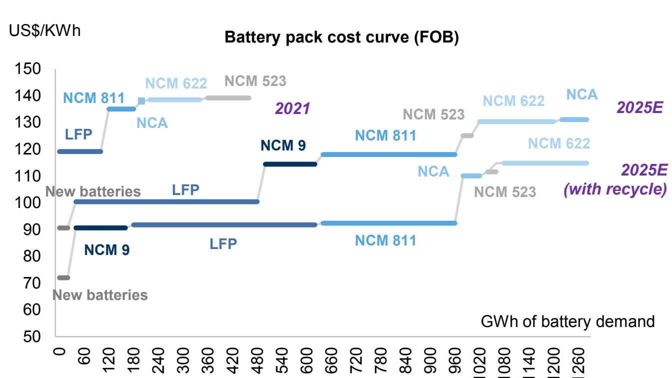
Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

Exhibit 21: Rising commodities prices offset ~40% of the cost deflation contributed by technology and chemistry improvement over 2020-25



Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

Exhibit 22: Battery technology development and recycling will likely flatten the 2025 cost curve between NCM vs LFP



Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

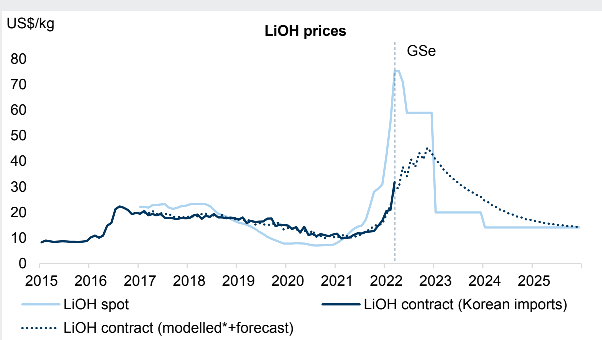
Box: Spot and contract lithium prices — which prices matter more for battery makers?

Spot and contract lithium prices have diverged meaningfully in recent months (Exhibit 23), leading to investors questioning which prices matter more for battery makers and how the contract prices are usually calculated.

Contract prices of lithium hydroxide are more relevant for high-nickel NCM cathodes (NCM 712, NCM 811, NCM 9/0.5/0.5, Exhibit 24). As per Wood Mackenzie, the lithium hydroxide market is dominated by contract-pricing. This is presumably due to the stringent specification of EV battery grade lithium hydroxide that requires a time-consuming and costly qualification process, which makes it difficult for buyers to purchase from the spot market. For lithium hydroxide supply contracts, there is typically a volume component and a price component, where the pricing is usually based on a basket of spot prices and earlier-month contract prices with a 3-6 months' lag. In regressions, we find that modeled series using spot prices with no lag and earlier-month contract prices with 2 or 4 months' lag closely match the historical Korean lithium hydroxide import prices (Exhibit 23).

Spot prices of lithium carbonate are more relevant for LFP and low-nickel NCM cathodes (NCM 532). Though it is difficult to pinpoint the exact market share, spot-pricing accounts for a much larger share of the lithium carbonate market than the lithium hydroxide market. This could be because lithium carbonate is used in a wider range of batteries (e.g. portable devices in addition to EVs) and is consumed by a large China-centric market that makes a liquid spot market possible.

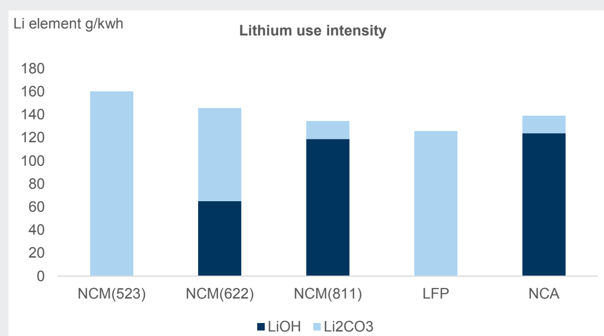
Exhibit 23: Spot and contract lithium prices have diverged meaningfully in recent months



*Modelled LiOH contract prices using a 2-month lag on earlier contract prices and no lag on spot prices

Source: Refinitiv, KITA, Goldman Sachs Global Investment Research

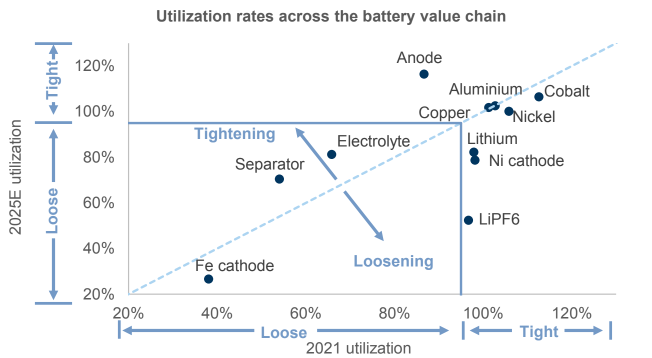
Exhibit 24: Lithium hydroxide is more relevant for high-nickel NCM cathodes; lithium carbonate is more relevant for LFP and low-nickel NCM cathodes



Source: Company data, Goldman Sachs Global Investment Research

Supply tightness ahead in anodes. Among battery components, we continue to see bottlenecks ahead in anode, where there is limited capacity in the pipeline, especially outside of China. We compare the battery demand outlook against the planned production capacity expansions across the various battery component markets, and find future supply of anodes to be relatively more constrained than other components. Based on new capacities announced so far, we assess that the effective utilization of anode capacity would increase from 87% in 2021 to 116% in 2025, indicating severe supply shortages. This will likely translate into a period of strong margins for anode production, driving more investment in anode for new capacities to be brought online over 2024-25.

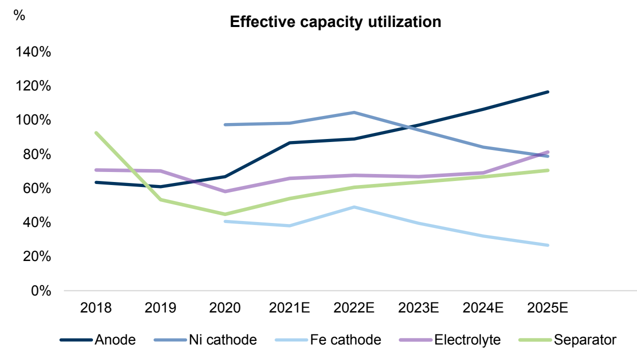
Exhibit 25: Along the battery value chain, supply is running most tight in base metals and anodes...



Demand / supply for raw materials; demand / capacity for processed materials and components; limited by forecast period, nickel and aluminium using 2023E for 2025E

Source: Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

Exhibit 26: ...from lack of anode capacity additions in the coming years (vs demand)



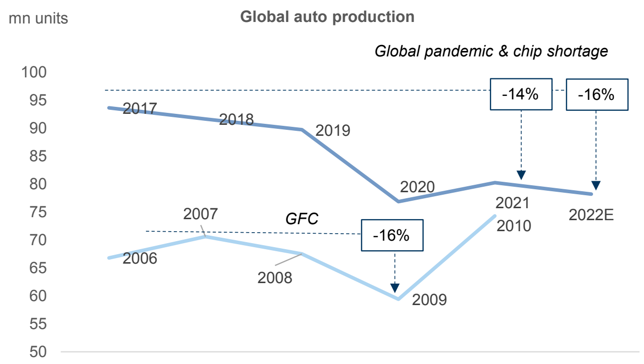
Source: Company data, Wood Mackenzie, SNE Research, Goldman Sachs Global Investment Research

#2: How would higher battery prices impact EV penetration?

Global demand for autos today sits ahead of supply; EV sales growth still tracking double-digit. Light vehicle production dropped to 77.2mn units in 2021, 19% below 2017's 95.1mn peak. While the 2021 level is already consistent with prior periods of market correction (-16%, 2007-09, Exhibit 27), our global Autos team sees further uncertainty around both auto production (slow progress resolving semiconductor shortages and delays with parts deliveries) and demand (macro environment in China, the US and India). Across regions, there is evidence in the form of record pricing and low inventories which supports that underlying demand could be higher than present production levels. EV sales continue to be the bright spot in broader car sales — while growth rates have slowed down from the 2021 levels, March sales were still up 29% yoy (Exhibit 28).

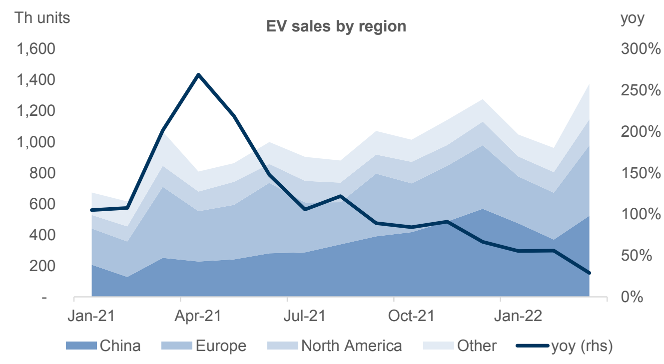
TCO (Total Cost of Ownership) analysis points to similar cost competitiveness of EV relative to ICE amid rising energy prices. Battery costs account for around 30% of total EV cost, and a reduction in these costs is essential for EV businesses to become economically viable. Strength in oil price supports EV sales even if battery prices fall less than previous expectations. We believe an EV premium payback period (i.e. the number of years needed for gasoline expense savings to cover the EV cost premium over an ICE) of around 3 years is a threshold for a new powertrain to be widely accepted by consumers. In the scenario of our base case battery price and YTD Brent oil price at US$105/bbl, we find the payback period to drop towards 3 years by 2025. As such, we keep our EV penetration forecasts largely unchanged, but nevertheless see the need to consider the downside risks to EV sales in a scenario where greenflation's impact is larger than our current base case as reiterated in our bear case scenario in Exhibit 31.

Exhibit 27: The decline in 2021 auto production is already consistent with prior periods of market correction, but uncertainty around both supply and demand leads us to be more cautious on the global autos outlook in 2022E



Source: IHS, Goldman Sachs Global Investment Research

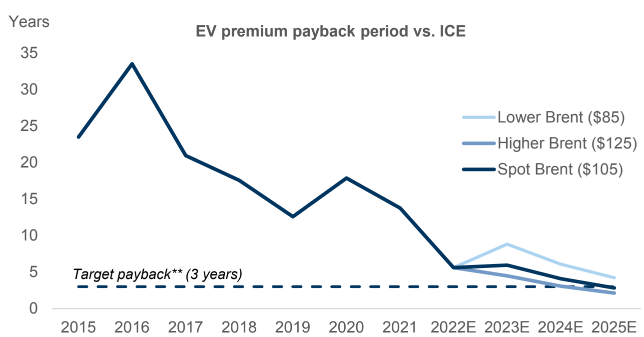
Exhibit 28: Global EV sales increased 29% yoy in March



Source: Wood Mackenzie

TCO analysis points to similar cost competitiveness of EV relative to ICE amid rising energy prices. As per our Europe Autos team, despite recent increases in electricity costs, similar increases in oil prices mean that costs for BEVs relative to ICEs have stayed broadly the same (Exhibit 30).

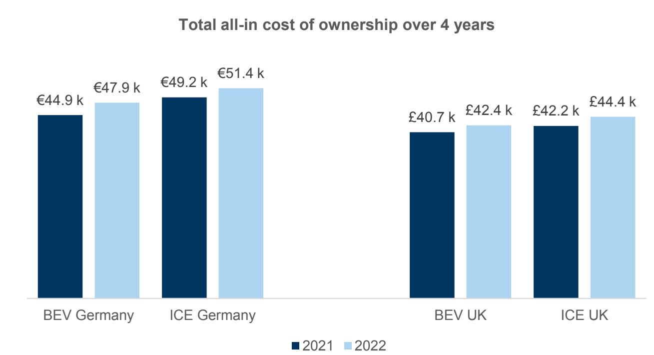
Exhibit 29: Even if battery prices fall less than previous expectations, the oil strength will likely support EV sales



*Toyota Prius achieved a breakthrough in sales after shortening the payback period to 3 years

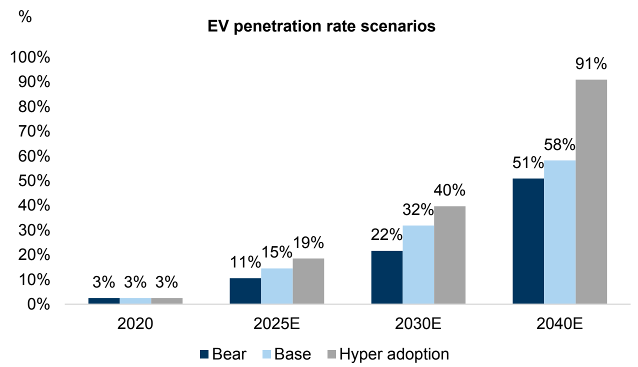
Source: Goldman Sachs Global Investment Research

Exhibit 30: Despite recent increases in electricity costs, similar increases in oil prices mean that costs for BEVs relative to ICEs have stayed broadly the same



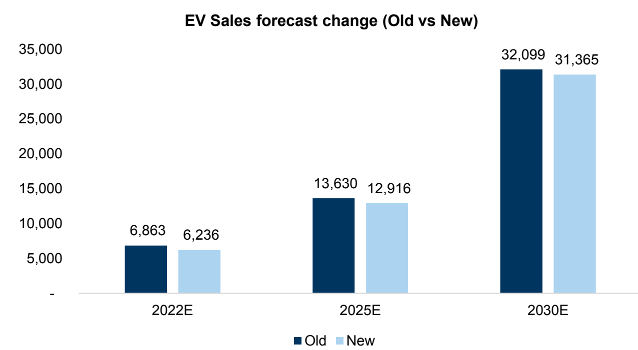
Source: Goldman Sachs Global Investment Research

Exhibit 31: We keep our EV penetration rates largely unchanged despite the cut to global automobile sales in 2022, 2023...



Source: Goldman Sachs Global Investment Research

Exhibit 32: ...leading to a lower number of EV sales



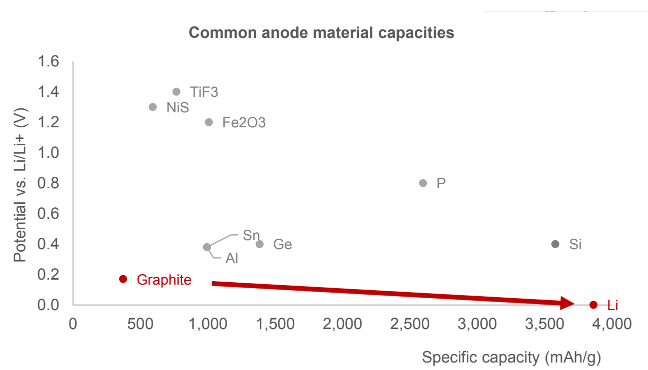
Source: Goldman Sachs Global Investment Research

#3: How are new innovations progressing in solid state batteries?

The greenflation increases the urgency for battery technology innovations which enables cost reductions. Among the new technology routes, solid state batteries caught widespread attention as a strong candidate for the next-generation battery. It is encouraging to us that more companies are working on solid state batteries, testing diversified technology routes. Still, further breakthroughs are needed for challenges such as improving the battery performance at room temperature, scaling up the cell layers to meet OEM requirements, and avoiding operational risks given the hazard which atmosphere air may cause to the Li metal and some solid electrolytes. The solid state battery makers that use Li metal as the anode generally target commercialization close to 2025 or in 2H20s.

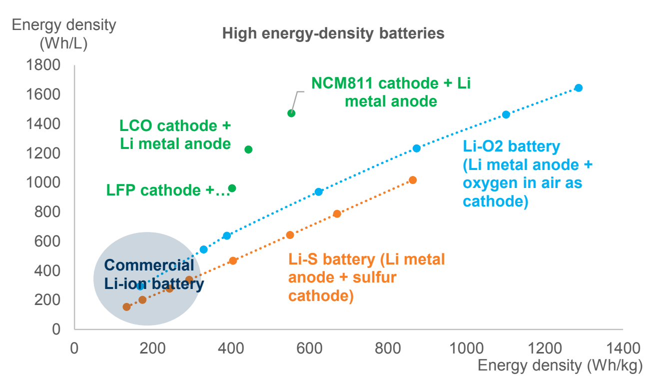
The greenflation increases the urgency for battery technology innovations that enables cost reductions. Among the new technology routes, solid state batteries (i.e. batteries that replace the liquid electrolyte and the separator with a solid electrolyte) caught widespread attention as a strong candidate for the next-generation battery. As discussed in "Box: Where does solid state batteries sit in the battery innovation roadmap?", solid state batteries unlock the potential of Li metal, the anode material of the highest energy density in nature (10 times of the capacity of graphite, Exhibit 33). The Li metal anode can potentially raise the battery energy density from c.200 Wh/kg (commercial batteries) to 400-500 Wh/kg with limited material changes required for the cathode, and towards >1000 Wh/kg with further cathode material changes (e.g. Li-O_2 batteries, Exhibit 34).

Exhibit 33: Li metal is the anode material of the highest energy density in nature and has 10 times the capacity of graphite



Source: Wu, et al. (2020)

Exhibit 34: Adoption of the Li metal anode can raise the battery energy density significantly higher than commercial LIBs



Source: Wu, et al. (2020)

How are the solid state battery innovations progressing? Many companies are working on solid state batteries, trying to achieve commercialization using different technologies (Exhibit 35-Exhibit 37). The solid state battery makers that use Li metal as the anode generally target commercialization close to 2025 or in 2H20s; others using alternative anodes (e.g. WeLion) are commercializing the products earlier but achieving lower energy density than the Li metal anode batteries (but still c.20% higher than top conventional LIBs). Since most of the benefits and future potential stem from the battery's ability to use Li metal as the anode, we categorize the solid state batteries by using or not using Li metal as the anode (as opposed to "solid"/"semi-solid"), and see the eventual adoption of Li metal anode in commercial production as a major milestone.

Exhibit 35: Many companies are working on solid state batteries, trying to achieve commercialization using different technologies

	Anode	Electrolyte/separator	Cathode	Energy density Wh/kg	Energy density Wh/L	Commercialization	Partnership
Solid /semi-solid state batteries potentially using Li metal anode							
QuantumScape	Li metal	Solid eletrolyte (ceramic) + gel catholyte	LFP (initial results)	300-450	950-1100	2024-25	Volkswagen
SES	Li metal	Anode coating + proprietary liquid eletrolyte + commercial separator	Commercial cathodes	370 (400+ projected)	700 (1000+ projected)	2025-28	GM, Hyundai
Solid Power	Li metal/Si	Solid eletrolyte (sulfide) + solid catholyte/anolyte	NCM	390-560	785-930	2024-26+	BMW, Ford
Toyota	Not disclosed	Solid eletrolyte (sulfide)	Not disclosed	Not disclosed	Not disclosed	2025	Panasonic
Samsung	Li metal	Solid eletrolyte (sulfide) + Ag-C separator	NCM		900+	2027 (may accelerate)	
ProLogium	Li metal/Si	Solid eletrolyte (oxide) + catholyte/anolyte	NCM	330 (lab)	850-880 (lab)	Not disclosed for Li metal	Mercedes-Benz, NIO
Nissan	Li metal	Solid eletrolyte (sulfide) + special protective films for anode + multilayer technologies to curb interface degradation	Cobalt-less cathode	c.500	c.1000	FY2028	Renault, Mitsubishi
LGES	Li metal Not disclosed Not disclosed	Not disclosed Solid eletrolyte (polymer) Solid eletrolyte (sulfide)	Sulfur-Carbon Not disclosed Not disclosed		c.900 600 900	Beyond 2025 2026 2030	Ongoing discussion Ongoing discussion Ongoing discussion
Honda	Not disclosed	Not disclosed	Not disclosed			Seconf half of the 2020s	SES (& independent research)
Solid /semi-solid state batteries using other anodes							
WeLion	C-Si	Solid and liquid eletrolyte + commericial separator	NCM (add LiTFSI, LLZTO)	360		2022-23	NIO
Ganfeng	Not disclosed	Solid (oxide) and liquid eletrolyte + separator	Not disclosed	260		2022	Dongfeng

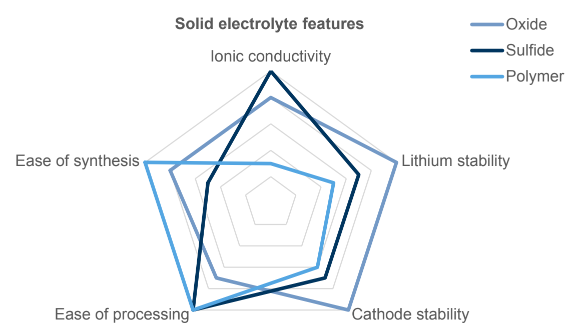
Source: Company data, Data compiled by Goldman Sachs Global Investment Research

Exhibit 36: Popular solid eletrolyte choices

Solid electrolyte type	Abbreviation	Chemical formula
Polymer	PEO	-[CH2-CH2-O]-n
Oxide	LLZO	$Li_7La_3Zr_2O_{12}$
	LLTO	$(Li, La)TiO_3$
Sulfide	Li2S-P2S5	Li_2S-P_2S_5
	LGPS	$Li_{10}GeP_2S_{12}$
Phosphate	LATP	$Li_{1+x}Al_xTi_{2-x}(PO_4)_3$
	LAGP	$Li_{1+x}Al_xGe_{2-x}(PO_4)_3$
Composite		PEO + $TiO_2/SiO_2/Al_2O_3$ or LLZO, LAGP

Source: Qi (2021)

Exhibit 37: Sulfide eletrolytes feature higher ionic conductivity while oxide eletrolytes are more stable with the Li metal anode



Source: Taylor, et al. (2019)

What are the future breakthroughs needed for solid state batteries? Among the multiple challenges to using Li metal as the anode with a solid electrolyte, we note companies have generally made progress in using solid electrolytes to suppress the Li dendrite issue of the Li metal anode (Exhibit 38). That said, remaining challenges include: 1) some solid state batteries require specific operating temperature and pressure (e.g. the Samsung battery requires 45-60 °C for designed discharge capacity[1]); 2) the solid state cells have to scale up from 1-4 layers to "dozens of layers" as required by the OEMs; 3) operational risks due to Li metal and solid electrolytes' sensitivity to the atmosphere air. Given the remaining challenges in designing and/or manufacturing solid state batteries, we see the possibility for a scenario where solid state could exist

[1] Lee, et al. (2020) High-energy long-cycling all-solid-state lithium metal batteries enabled by silver–carbon composite anodes

but be costly in the early years and used mostly in premium cars.

Exhibit 38: Multiple challenges exist to using Li metal as the anode with a solid electrolyte

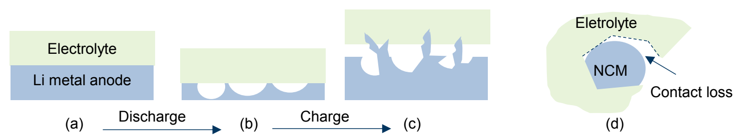
"?" indicates areas that remain to be addressed by the solid state battery makers

Challenge details

Challenges of Li metal anode

Unstable form/structure of the anode: During charging, uneven Li deposition on the surface of the anode tends to form dendritic crystals and dead Li. Unlike in liquid eletrolyte batteries, where Li dendrite could puncture the separator and lead to short-circuit of the battery, the mechanical strength of the solid eletrolyte may stop the penetration of the Li dendrite (chart c)

Volume change of the anode: Ideally all the Li metal will be ionized and transported into the cathode after completing the discharge, causing anode volume changes. Together with Li dendrite, it leads to interface fluctuation of Li metal and the eletrolyte, which impairs the Li+ ion flow at the interface and limits energy density (chart b & c)



Li metal sensitivity: Li metal reacts with moisture and oxygen in the air which may cause fire/explosion. ?

$2Li + 2H_2O = 2LiOH + H_2 (g)$ $4Li + O_2 = 2Li_2O$

Challenges of solid eletrolytes

Poor solid-solid contact: During volume changes of the anode and other active materials, the poor solid-solid contact between electrodes and the solid electrolyte impairs the Li+ ion flow at the interface which limits energy density (chart d)

Side chemical reactions: chemical reactions at the interface of the electrode and the solid eletrolyte causes active material losses

Solid eletrolyte sensitivity: H_2O, O_2 and CO_2 attacks cause degradation in the solid eletrolyte ?

Operating environment: May require specific operating temperature or pressure ?

Scaling up: From 1-4 layers to dozens of layers as required by the OEMs ?

Company efforts

- QuantumScape: ceramic electrolyte with high dendrite resistance
- Nissan: protective films for the Li metal anode
- SES: utilized composite anode coating as a mechanical barrier
- Samsung: a thin Ag–C layer can effectively regulate Li deposition, avoiding dendrites and dead Li
- Samsung: the soft and elastic mechanical properties of the argyrodite electrolyte facilitates an intimate contact between the electrolyte and the electrodes.
- QuantumScape: coupled the solid ceramic eletrolyte with an organic gel electrolyte for the cathode. The latter makes good contact with cathode
- QuantumScape: the solid ceramic eletrolyte is stable to Li metal
- Samsung: applied a thin Li2O–ZrO2 (LZO) coating on the NCM cathode, to avoid the cathode-eletrolyte side reactions; utilized a layer of carbon to separate the eletrolyte from Li metal
- Nissan: testing both wet and dry processes for the adoption of sulfide solid electrolytes; extremely difficult to convert its current liquid-based LiB production line into one that can produce ASSBs.
- QuantumScape and SES batteries operate at 25-30°C, while the Samsung battery requires 45-60 °C (pending lowering the interfacial resistance and increasing the ion conductivity of the solid electrolyte)
- QuantumScape has tested making 16-layer solid-state cells

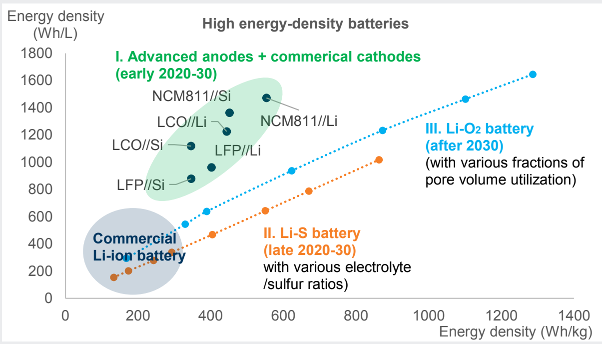
Source: Company data, Goldman Sachs Global Investment Research

Box: Where do solid state batteries sit in the battery innovation roadmap?

A solid electrolyte enables the anode material change from graphite to Li metal. Future high energy-density batteries generally focus on three technological routes (Exhibit 39): 1) early 2020-30: advanced anode batteries (replacing the graphite anode in commercial batteries with Li metal anode or silicon anode to pair with commercial cathodes), 2) late 2020-30: Li-S batteries (further replace the commercial cathodes with sulfur to pair with the Li metal anode) and 3) after 2030: Li-O_2 batteries (pairing oxygen in the atmosphere air as cathode with the Li metal anode). To enable the anode material change from graphite to Li metal used in all these three routes, a solid electrolyte is usually required (not necessarily for silicon anodes[2]). This is because the Li metal anode tends to generate Li dendrite on the surface of the anode that could penetrate through the liquid electrolyte and the polymer separator, causing short circuit of the battery, whereas the mechanical strength of a solid electrolyte can suppress the dendrite issue (Exhibit 40).

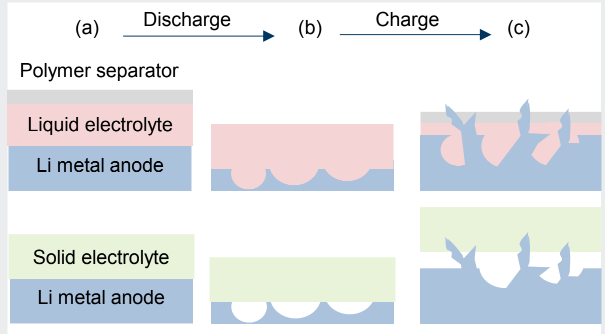
[2] Zhang, et al. (2021) Challenges and Recent Progress on Silicon-Based Anode Materials for Next-Generation

Exhibit 39: Future high energy-density batteries mostly focus on three technological routes



Source: Wu, et al. (2020), Mckinsey, Goldman Sachs Global Investment Research

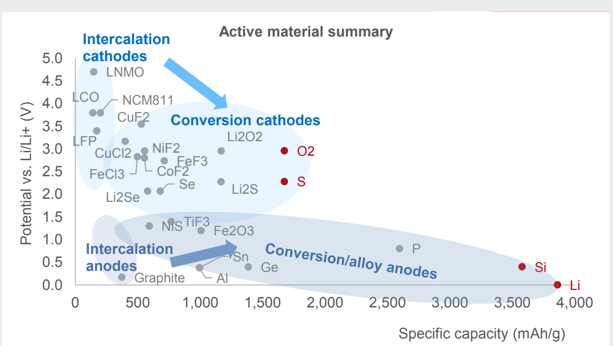
Exhibit 40: Li metal anode tends to generate Li dendrite on the surface of the anode; the mechanical strength of a solid electrolyte can suppress the dendrite issue



Source: Goldman Sachs Global Investment Research

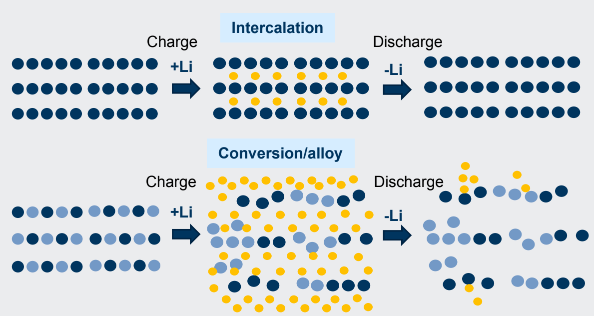
Li metal offers the highest energy density among the possible anodes. Beyond the above-mentioned three technological routes, there are plenty of other possible combinations of cathode and anode materials — the general direction being moving from intercalation materials (e.g. NCM/LFP for cathode; graphite for anode) to conversion/alloy materials (e.g. S for cathode; Si/Li for anode). Among the possible conversion/alloy anode materials, Li metal provides the highest theoretical discharge/charge capacity (Exhibit 41). Conversion/alloy materials (per unit) typically can store a larger amount of lithium than intercalation materials, leading to higher energy capacities. However, such lithium storage requires altering or breaking host material atomic bonds, which could result in large volume changes (e.g. for Si anodes), or a large amount of lithium being deposited on the surface of the host material (Li metal anode's dendrite issue, Exhibit 42).

Exhibit 41: Li metal offers the highest energy density among the possible anodes



Source: Wu, et al. (2020)

Exhibit 42: Conversion/alloy materials per unit can store more lithium than intercalation materials, leading to higher energy capacities; however, volume changes and Li dendrites are typical issues



Source: Lee, et al. (2020)

#4: How will supply chain complexity impact new startups, and will the battery industry remain consolidated?

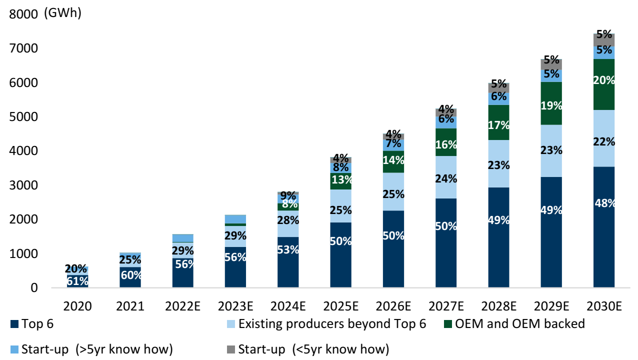
Although a number of new startups are competing for market share in cell manufacturing, we do not see a significant risk for top players to maintain leadership over 2022-30. In our view, multiple barriers exist for new entrants including incumbent top players' technology leadership, economies of scale, and their extensive vertical integration, which ensures full control of the supply chain — a competitive strength that becomes more prominent in the face of the raw material supply bottlenecks.

The cell manufacturing industry ex-China will likely remain tight through 2025. Although cell manufacturing in general will likely see overbuilt capacity during 2022-25, with the global average utilization declining towards 57% by 2025, we note the ex-China market will likely remain tight, with utilization above 100% over 2022-25. In this analysis, we consider the company-level capacity expansion announcements, as well as the historical utilization of the respective companies, to incorporate into a yield-adjusted effective capacity outlook for the cell manufacturing industry.

Top cell manufacturers to maintain leadership in ex-China over 2022-30. Although new technologies and startup companies are emerging in cell manufacturing, we do not see a significant risk to top players maintaining leadership over 2022-30. In our view, multiple barriers exist for new entrants, including incumbent top players' technology leadership, economies of scale, and their extensive vertical integration, which ensures full control of the supply chain. The current raw material bottleneck gives rising importance to vertical integration of cell manufacturers, where the top players can establish long-term raw material access more easily than start-ups can, leveraging their scale and existing relationships with the upstream. Further, skilled labor shortage, which is an issue even for the large incumbents (e.g. LG Chem), imposes additional challenges for start-ups to ramp up mass production. As such, we expect non-OEM-backed start-ups to account for only 2-3% of global supply in the coming decade, and the industry to remain consolidated.

Exhibit 43: We estimate global battery players' announced capacity plans could reach c. 7.4TWh by 2030E...

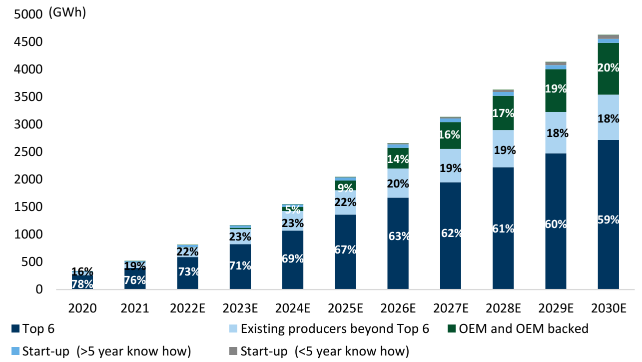
Global battery players' announced capacity outlook



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 44: ...with yield adjusted capacity at 4.6TWh

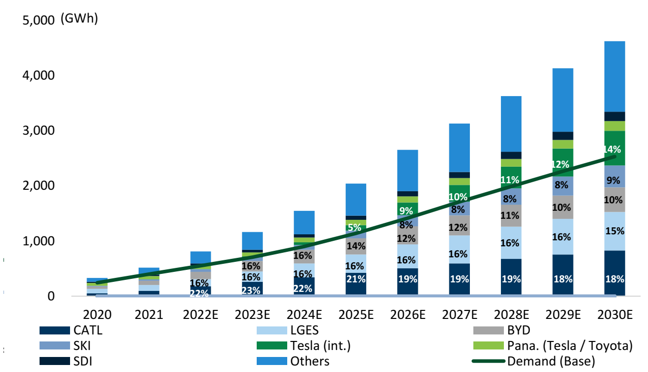
Global battery players' yield adjusted capacity outlook



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 45: Yield adjusted battery capacity on a global level shows loosening battery supply-demand over the coming years

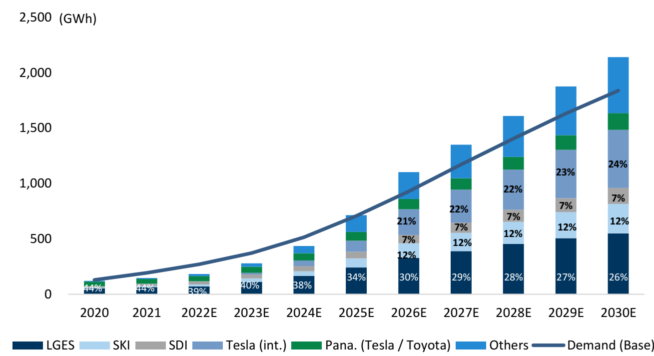
Global key battery players' yield adjusted capacity outlook vs base demand outlook



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 46: ...while we expect ex-China supply to remain tight

Key battery players' yield adjusted capacity (ex-China) outlook vs base demand outlook (ex-China)



Source: Company data, Goldman Sachs Global Investment Research

#5: Has bargaining power shifted from OEMs to battery makers? When would battery maker margins bottom out?

Power balance between battery makers and automakers

Market concentration is higher among battery makers than it is among finished vehicle makers. As of 2021, the top 6 global finished vehicle assemblers accounted for just 56% of total sales, whereas the top 6 battery makers accounted for 84% of sales. This naturally gives the battery makers an advantage when it comes to negotiating prices. Battery makers are adopting price adjustment systems for nickel, cobalt, and lithium to mitigate the impact of greenflation, and some battery makers are expanding their price adjustment system to other materials (copper, mangan, aluminum, etc) as well.

Korea Battery makers' price pass-through mechanism

Korea EV battery makers have made robust contracts for both the raw materials sourcing through strategic partnerships and also long term materials contracts with OEMs. This was witnessed in 1Q22 results with in line to above expectations margins for LGES and Samsung SDI. All three major Korea EV battery players (LGES, SDI, SKI) have already made cathode metals (Nickel, Cobalt and Lithium) as a pass-through to OEMs in the contracts signed over the last few years. LGES management highlighted an expanded pass-through scheme of non-cathode materials (Copper, Aluminum, Mangan) partially to the OEMs. That said into 2Q22 results investors should monitor the time lag of ASP increases and lack of potential offsets from low-cost inventory. Nevertheless, with cathode metals pass-through structures and with the battery metals bull market peaking out, we expect OP margins for battery makers to bottom out into 2Q22.

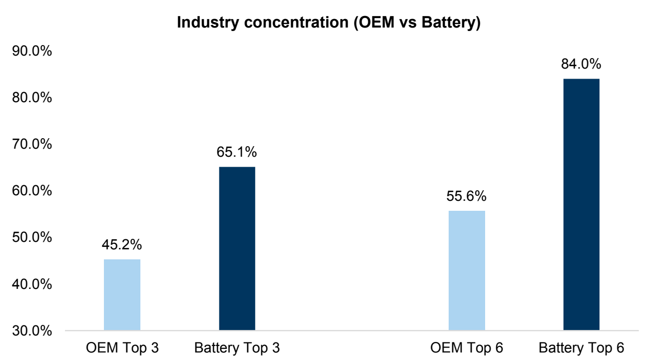
China battery makers' industry structure

The Chinese EV industry differs from the rest of the world in that the country has incubated a full supply chain of battery materials, with CATL leading the market share but also competing with other domestic local battery makers with large (>20GWh) capacities. In addition, the country's EV industry is led by BYD which has a 30% vehicle market share and relies exclusively on in-house batteries. Therefore, depending on if a carmaker is volume focused (e.g. SAIC) or cost focused (e.g. Tesla), the tolerance of higher battery prices varies by company. This is in contrast to the EV market outside China where battery-making is more consolidated than carmaking, where a robust pass-through of input costs to automakers is standard practice for major EV battery players. Specifically, the Chinese industry is characterized by:

- **Fragmentation of supply in battery making:** CATL's market share of domestic EV power battery installation has fallen from 57% in Dec 2021 to 37% in Apr 2022. On an ex-Tesla (bumpy monthly volume due to export demand) and ex-BYD basis, CATL's market share has fallen from 64% in Dec 2021 to 52% in Apr 2022. Meanwhile, BYD and other smaller battery makers have gained share: BYD's share went from 15% in Dec 2021 to 29% in Apr 2022, CALB from 5% to 8%, Guoxuan High Tech from 4% to 6% (source: GGII). In addition, top EV makers are diversifying battery sourcing in order to manage supply chain cost and risk: Xiaopeng, for example, from which CATL has supplied 79% of its batteries in Dec 2021, has diversified the battery supply with the latest split of 52% / 42% / 5% from CATL / CALB / Eve Energy, respectively in Apr (source: GGII).

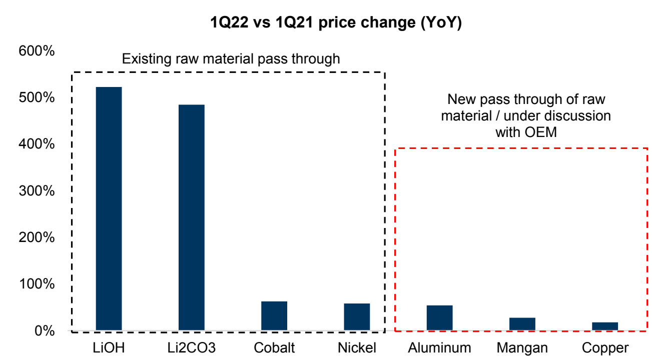
- **Acceleration of demand in NEV assembly:** The new energy vehicle market in China has tripled in volume from 1mn in 2020 to 3mn in 2021, and we model another +74% yoy growth in 2022E to 5.2mn units. In this rapidly evolving market, carmakers are mostly market share focused and therefore have high tolerance of battery prices. But since the demand is booming and access to battery is strategic to production planning, EV makers are exploring second or third suppliers of power batteries.
- **BYD drives new technologies, such as cell to pack and cell to body, on the back of its integrated battery making + car making:** This is difficult for other EV makers to replicate given they procure battery packs externally and integrate to their chassis – they cannot coordinate the design between battery architecture and car body.
- **Uncertainties of lockdown-related supply and macro-led demand:** The Covid Zero policy has led to the lockdowns of top car manufacturing sites in Shanghai and Changchun.

Exhibit 47: The EV battery industry is more consolidated vs the OEM industry
Industry concentration (OEM vs battery) in 2021



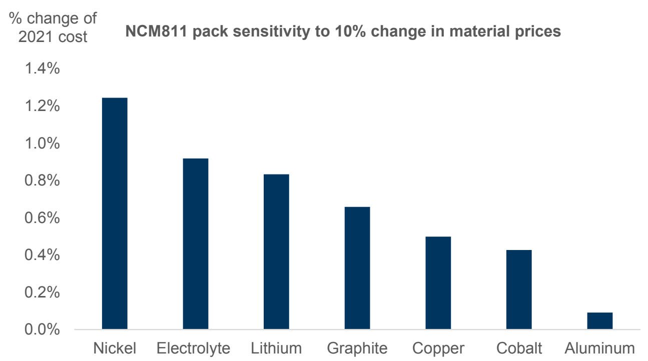
Source: Goldman Sachs Global Investment Research, SNE Research

Exhibit 48: Korean EV battery makers are actively working on expanding pass-through contracts...
Price change of raw materials & pass-through of raw materials to OEMs



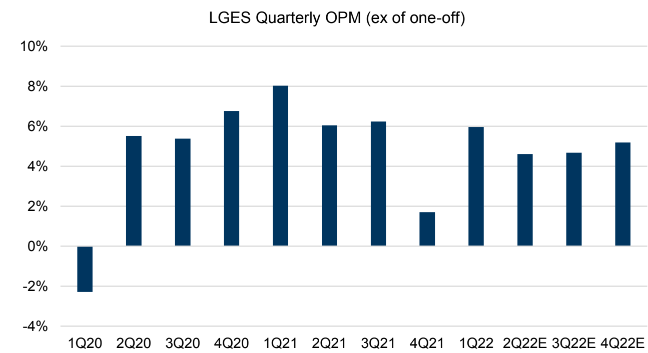
Source: WIND, LME, Company data, Goldman Sachs Global Investment Research

Exhibit 49: ...which will protect them from material price inflation...



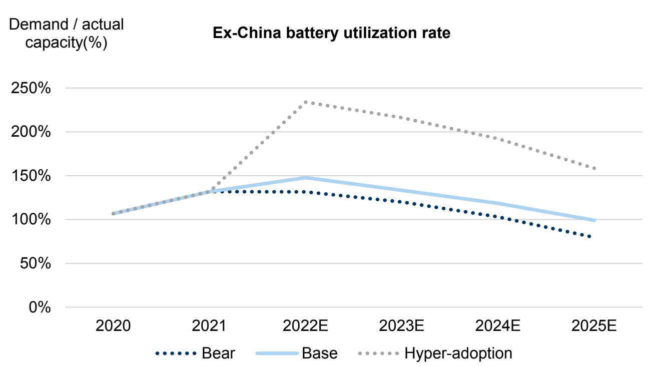
Source: Company data, Wood Mackenzie, Goldman Sachs Global Investment Research

Exhibit 50: For Korea pure play battery maker LG ES we expect margins to bottom out in 2Q22



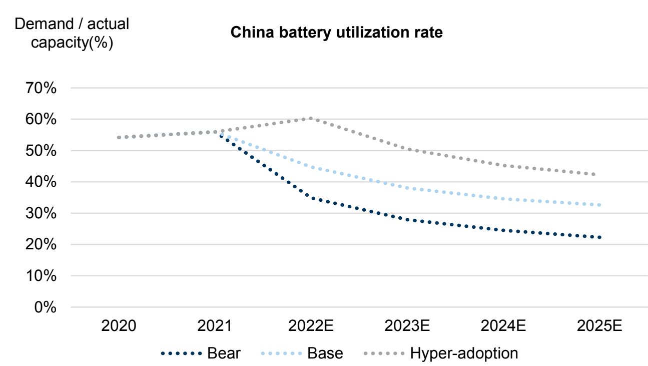
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 51: The Ex-China battery market is still tight which gives more bargaining powers to players (ex-China)...
Ex-China battery utilization rate



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 52: ...while there appears to be ample battery supply in the China market due to existing capacity and capacity future expansion plans
China battery utilization rate



Source: Company data, Goldman Sachs Global Investment Research

#6: How do we see the competitive positioning and valuation risk-reward of battery companies?

Strong competitive positioning for LGES and CATL, but valuation risk-reward is not compelling: LGES is a leader in the European market and is expanding to the US, while CATL is the largest battery manufacturer in China (by mkt share), with plans to export and expand overseas. Both companies have a strong technological edge, with vertical integration through investment and in-house production. CATL leads in terms of cost structure with a concentrated battery supply in China reducing operating and working capital costs. However, we expect the gap in margins and working capital to trend down as LGES (along with LGC) further integrates vertically while CATL expands internationally. LGES leads in terms of diversification towards global top-tier OEMs and higher exposure in the ex-China market where supply-demand is likely to be tighter.

Exhibit 56: LGES is a leading player in NCM pouch battery while CATL leads in NCM & LFP prismatic battery...
LGES vs CATL Technology

	LGES	CATL
Battery form factor	Pouch / Cylindrical	Mainly Prismatic (c.1% sales from Pouch)
Battery chemistry (Current)	NCM/NCMA	NCM & LFP
Battery chemistry (Developing)	**Lithium sulfur (from 2025):** High energy density (1.5x vs existing LiB) battery with lower cost, tested in unmanned plane **Solid state (Polymer based / Sulfide based: from 2026/2030):** High energy density (600Wh/L, 900Wh/L) with high charging speed using solid state electrolyte **LFP battery:** Developing for ESS, R&D for low range EV	**Sodium ion battery (from 2023):** Energy density of up to 160Wh/kg (1st gen) / 200Wh/kg (2nd gen), with charging time in 15 minutes to 80% SOC **Cell to Chassis:** Integrates the battery cell with the vehicle body, chassis, electric drive, thermal management extending driving range to over 1,000km

Source: Company data, Goldman Sachs Global Investment Research

Exhibit 57: ...with both having a diversified supplier base (as of 2021)...
LGES vs CATL key battery materials suppliers

	LGES	CATL
Battery materials supplier	**Cathode: LG Chem**, Poscochem, L&F, Nichia, Umicore **Anode:** Poscochem, BTR, Hitachi, Zichen, Shanshan, Mitsubishi **Separator: LG Chem** JV with Toray, SKIET, Toray, Asahi, Semcorp **Electrolyte:** GTHR, Capchem, Tinci, Enchem, Ube, Central Glass	**Cathode:** Ronbay, XTC, Zenhua **Anode:** BTR, Zichen, Shanshan, Kaijin, XFH, Shinzoom **Separator:** Semcorp, Senior, Sinoma, Mingzhu, Toray, SKIET **Electrolyte:** GTHR, Capchem, Tinci, Kaixin, Shanshan

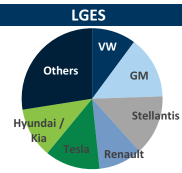
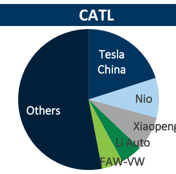
Source: Company data, SNE Research, compiled by Goldman Sachs Global Investment Research,

Exhibit 58: ...as well as strong vertical integration through in-house manufacturing, JV, investment, etc
LGES vs CATL vertical integration (as of 2021)

	LGES	CATL
JV / MOU / Equity stakes	**MOU with the Indonesian government:** LGES to build battery plants in Indonesia, while getting stable supply of Nickel in Indonesia. **QPM:** Through an investment of W12bn, LGES acquired a 7.5% stake in QPM, from which it will get supply of 7k tons of nickel, 0.7k tons of cobalt from 2023 for 10 yrs **Greatpower Nickel & Cobalt**: Through an investment of W35bn, LGES acquired 4.8% stake, from which it will get supply of 20k tons of nickel from 2023 for 6 yrs **Cobalt Blue:** LX International (LG's group company) owns 6% of Cobalt Blue (company supplies cobalt to LGES).	**Neo Lithium:** Through a $6.7mn investment, CATL acquired 8% stake **North American Lithium**: CATL acquired a 43.59% stake in Mar 2018 **Tianyi Lithium**: CATL owned 25% of Tianyi Lithium 9lithium salt producer in China), and invested Rmb 700mn in setting up a JV. **Zhicun Lithium:** In Sep 2021,CATL participated in Zicun's (lithium carbonate producer) equity placement and holds a 8.16% stake. **Pilbara Minerals**: CATL bought 8.5% of Australian company Pilbara Minerals, as part of a $61.8 million capital raising **North American Nickel**: CATL acquired a 25.4% stake **Electrolyte (Yongtai Technology):** CATL holds 25% of Yongtai. The entity now has capacity of 6k tons of LiPF6 and 400 tons of LiFSI
In house	**Cathode:** LGC (parent company of LGES) currently provides 25% of LGES required cathode, and aims to increase this portion to 30-40% **Separator (JV with Toray):** LGC plans to make 800mn m2 separator capacity in a JV with Toray by 2028, while LGC currently owns a separator coating business **Carbon Nanotube (CNT):** LGC plans to expand CNT capacity from 1.7k tons to 2.9k tons in 2023 **Anode Binders:** LGC currently provides anode binders to LGES	**Cathode (JV with Dynanonic)**: In Jan 2021, CATL and Shenzhen Dynanonic signed an agreement with the Jiang'an (Sichuan) government to build a LFP cathode plant with a capacity of 80 tpy. **Anode**: Phase 1 Project of 430 ton annual production of silicon anode via Pingnan Contemporary (100% subsidy of CATL) was completed in 2019 and Phase 2 now in construction. **Anode (BAIC)**: CATL established Pride Power with BAIC, with CATL holding a 25% stake to develop natural graphite. **Electrolyte additive: (Longyan Sicong)**: CATL holds a 66% stake and develops fluorine-containing additive via the entity.
Long term contract	**Vulcan Energy:** 5yr contract (2025-2029) for 45k tons of lithium hydroxide. **Australian Mines:** 6yr contract for 71k/7k tons of Nickel, Cobalt **Chemco:** 10% stake in Korea Zinc's Nickel sulphate subsidiary (Chemco). **Zhejiang Huayou Cobalt:** JV with Huayou Cobalt to establish precursor and cathode material facilities (40k tons expanding to 100k tons). **Tianqi Lithium:** Supply lithium hydroxide which will cover 15% of production capacity at TLK's lithium hydroxide project in Kwinana from 2020 to 2022, with an option to extend the deal by 3yrs.	**Ronbay:** Signed an agreement with this high-nickel cathode manufacturer to purcase 10k tons of cathode in 2022. **BASF**: CATL and BASF announced a strategic partnership on battery materials solutions, including cathode active materials (CAM) and battery recycling, in support of CATL's localization in Europe **Glencore:** In 2017, CATL struck a deal with cobalt supplier Glencore for it to sell up to 20,000 tonnes of cobalt products over 4 years **GWM**: In June 2021, CATL and Great Wall Motor signed 10-year strategic cooperation agreement to promote the development of new energy vehicle technologies
Recycling	**Li-cycle:** W30bn investment each (LGES/LGC) acquiring total 2.6% stake. Through this investment, LGES/LGC will source 20k tons of Nickel for 10yr (from 2023) **Ecopro:** LGES to provide used battery (20k tons) in Korea to Ecopro from 2024	**Brunp**: CATL owns a 65% stake in Guangdong Brunp, and invested Rmb32bn in Hubei Yichang Battery Material Vertical Integration Project, which recycles battery materials including LFP / NCM precursors, LFP / NCM cathode, anode, etc

Source: Company data, data compiled by Goldman Sachs Global Investment Research

Exhibit 59: LGES has a more diversified mix of clients, while CATL is more focused on China
LGES vs CATL client mix

	LGES	CATL
Key clients mix (LGES 2025, CATL 2021, China only client mix)		
Key EV models	Tesla Model 3, Y (China), VW ID.3, 4, GM Hummer, Renault Zoe	Tesla Model 3, Y (China); Nio ES6,8,EC6; Li Auto Li One; Xiaopeng P7,5,G3
Geographical mix (by capacity location)	Europe: 54% (2020), 21% (2025E) US: 4% (2020), 47% (2025E) China: 33% (2020), 24% (2025E) Others: 8% (2020), 8% (2025E)	China: 100% (2020), 96% (2025E) Europe: 0% (2020), 4% (2025E) [Export from China: 32% (2020), 32% (2025E)]

Source: Company data, Goldman Sachs Global Investment Research

Disclosure Appendix

Reg AC

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