Powertrain 2020

The Li-Ion Battery Value Chain – Trends and implications

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Strategy Consultants

August 2011

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Agenda

A **MARKET DEVELOPMENT:**
We expect that by 2020 xEVs sales volume can capture up to 8% .. 10% of global sales, provided battery costs come down

B **CURRENT VALUE CHAIN:**
Cell manufacturing and processing of active materials represent major parts of current costs – value chain today dominated by Asian players

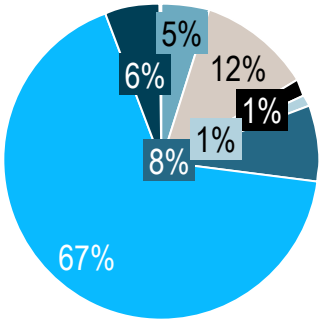
C **BATTERY COST AND VALUE CHAIN DEVELOPMENT:**
With battery costs decreasing down to 250 USD/kWh in 2020, the value chain is expected to consolidate and to develop a clearer tiered structure

D **IMPLICATIONS:**
The LiIon-battery value chain will change dramatically, automotive companies need to reflect these dynamics in products, partnering strategies and processes

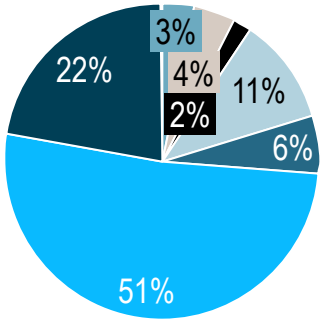
We expect that by 2020 xEVs sales volume can capture up to 8% .. 10% of global sales, provided battery costs come down

Share of powertrain technologies in major markets in 2020 – High scenario [%]

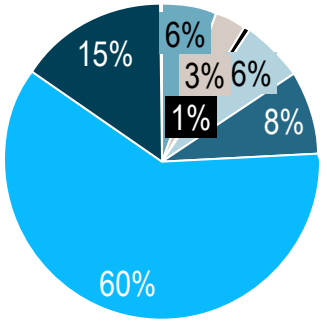
WESTERN EUROPE



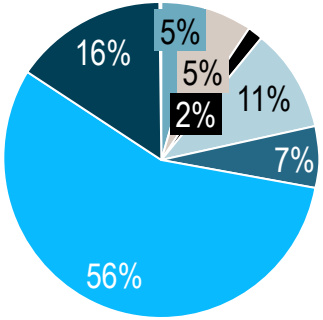
NORTH AMERICA



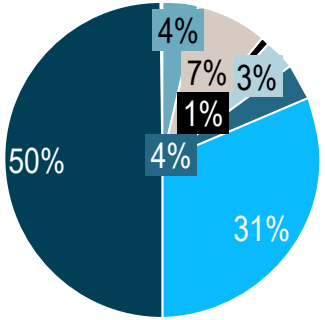
JAPAN



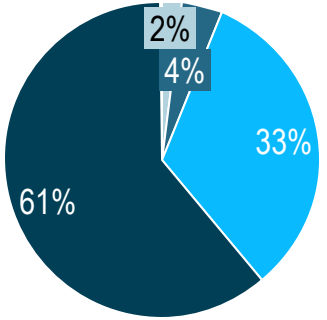
KOREA



CHINA



ROW



EV | PHEV serial | PHEV parallel | Full hybrid | Mild hybrid | Micro | ICE

Source: Roland Berger

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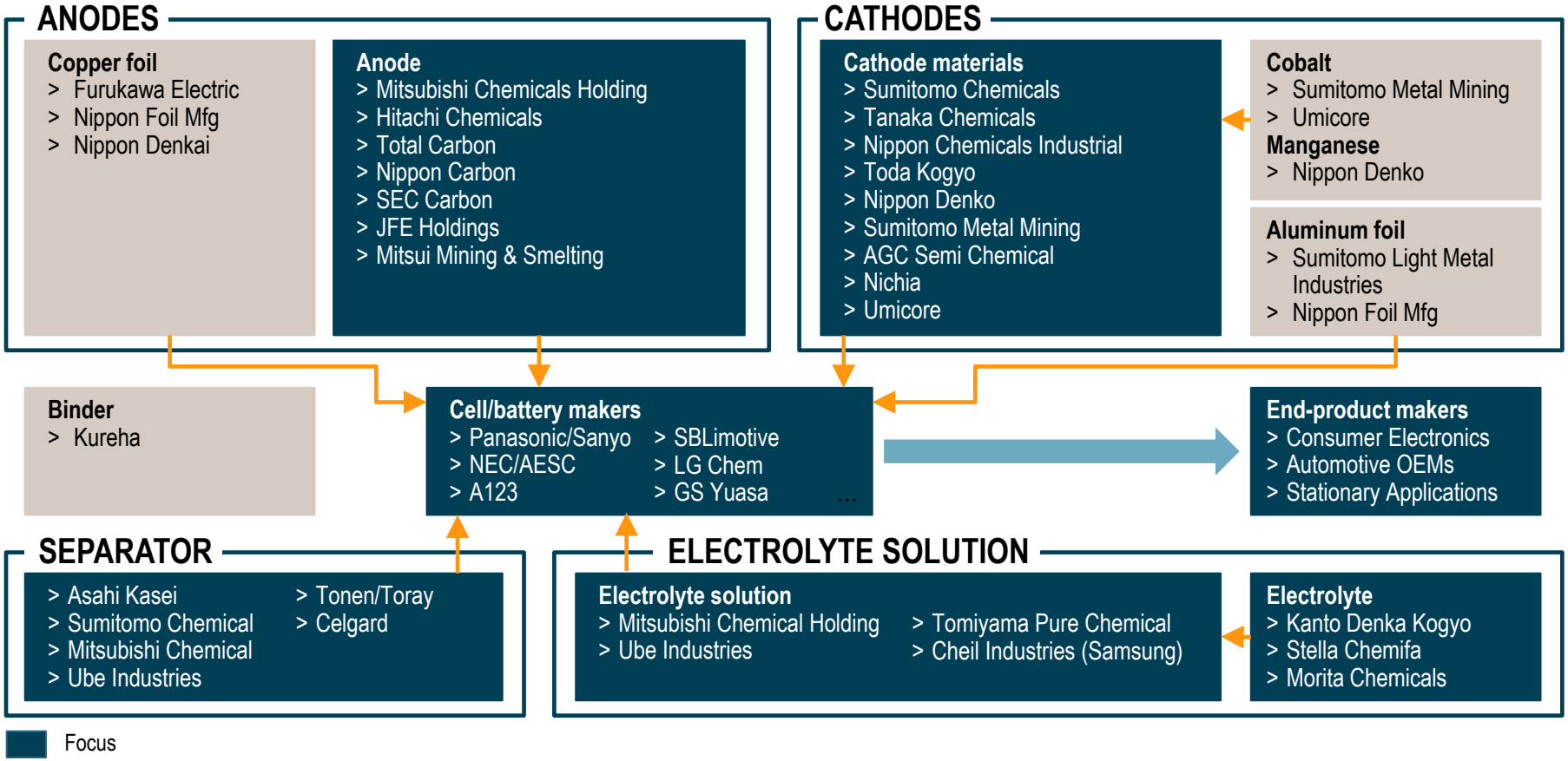
To understand cost development the industry structure and future trends need to be understood

Li-Ion battery supply chain overview

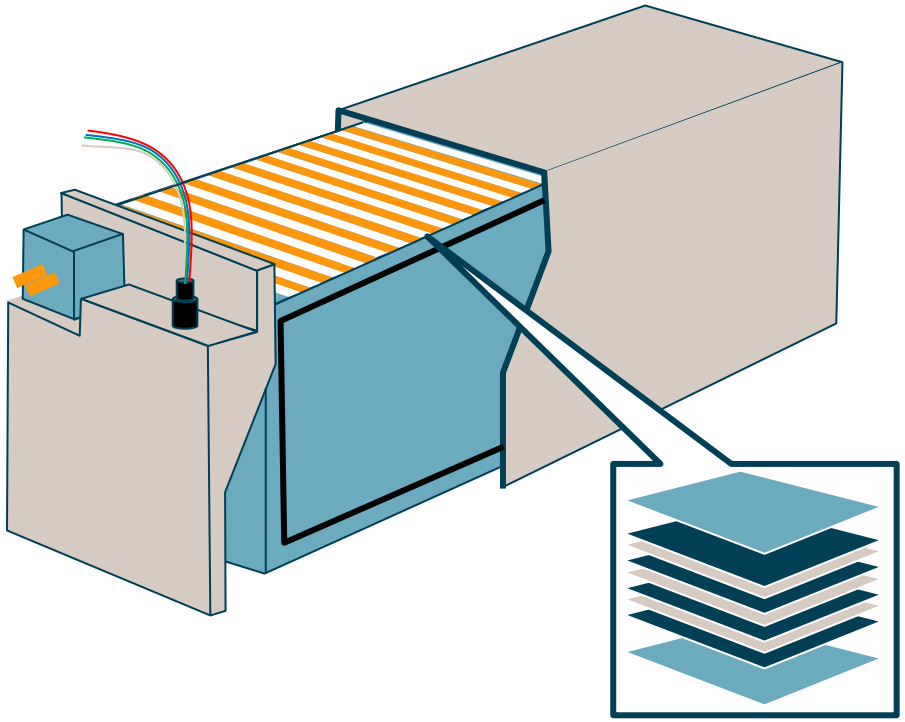


Source: Roland Berger "LIB value chain cost model"

We use a realistic high-energy reference battery for our unique cost analysis covering the complete value chain

Reference battery module used in analysis

BATTERY MODULE DESIGN



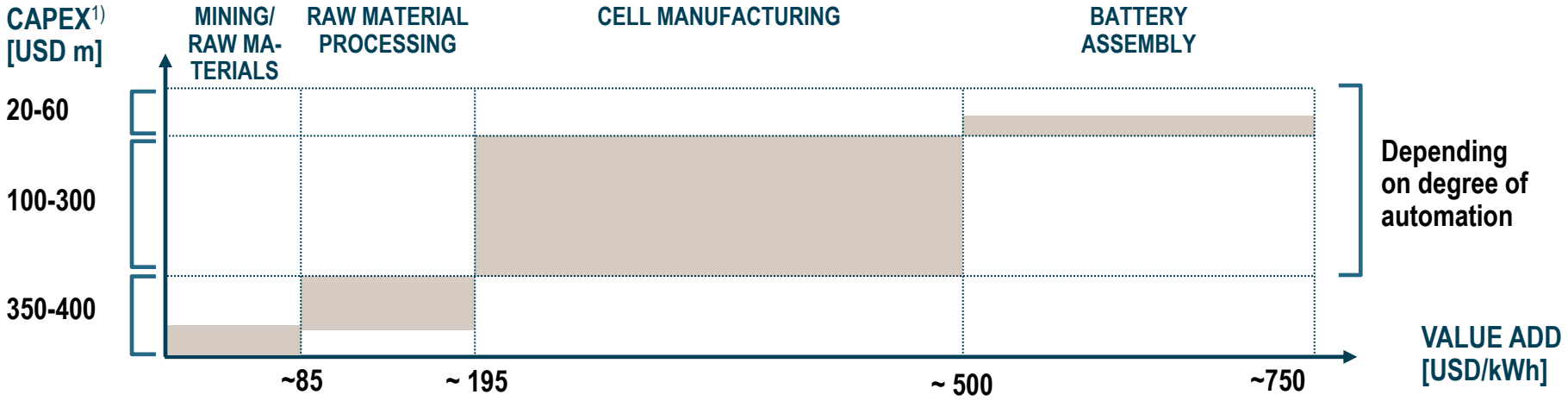
MAIN SPECIFICATIONS

- 266 V/ 20 kWh battery
- 2 parallel strings with 6 modules in series for each string; (12 modules in total) = 20 kWh
- Battery module: 44 V/38 Ah = 1.67 kWh
- Module weight: 13 kg
- Total battery weight with BMS etc.: 176 kg
- Integrated liquid cooling with heat conducting plates between cells
- Integrated module controller, monitoring each cell

Source: Roland Berger "LIB value chain cost model"

Raw materials and processing account for around 40% of cell costs – High lever for future cost reduction efforts

Value chain EV battery of ternary mix (NMC), current costs



PRODUCTION	> Local	> Global[2]	> Regional	> Local
COST DRIVERS	> Material purity (to/m^3)	> Specific energy (kWh/kg)	> Production efficiency (m^2/sec)	> Volume (n/hrs)
LEVERS	> Mining capacity (oligopoles) > Sulphatization	> Standardization > New materials > Process technology	> Manufacturing technology	> Assembly technology > Labor costs > Component costs

1) Necessary invest for 100 k EV-equivalents (20 kWh) 2) Electrolyte solutions will be produced in region, electrolytes ($LiPF_6$) can be produced in a single location for global market

Source: Roland Berger "LIB value chain cost model"

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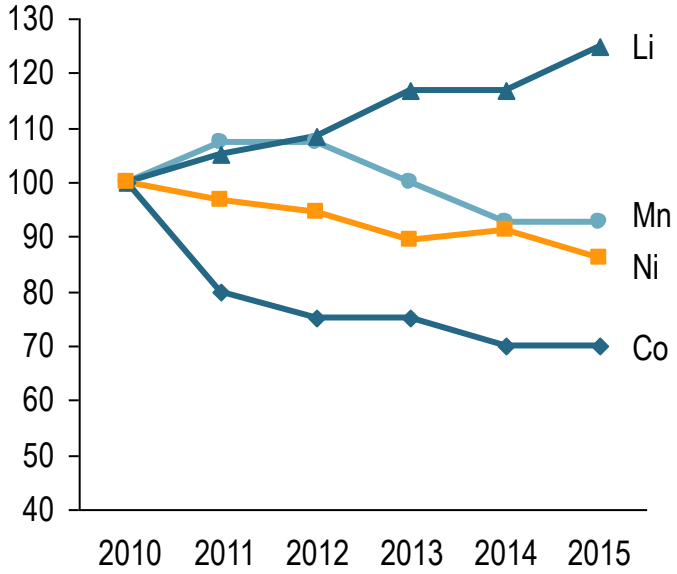
Co and Ni prices are expected to decrease as capacity is expected to double – Positive effect on cathode material cost

Expected raw material price development 2010-2015 (2010 = 100%)



	Price 2010 [USD/kg]	Price 2015 [USD/kg]	Long-term [USD/kg]
Li	7.0	8.8	9.3
Mn	8	7.4	6.3
Ni	22	18.9	17.7
Co	48.0	33.6	26.4

Li: $LiCO_3$ with 19% Li content
Mn: High grade (44%) content
Ni: 99.8% Ni content (LME)
Co: 99.3% Co content (LME)

COMMENTS

- Increasing **nickel capacities**, production of cobalt as a by-product
- **Cobalt capacity** expected to **double** by 2015
- **Lithium price** expected to **increase** until 2015, as only limited capacities built up yet
- **Price premiums for sulphatization** processes (esp. for manganese) **expected to stay high**

Source: Roland Berger "Battery material cost study V.2.4 / Q1 2011"

While Top-3 companies share 60-80% of the market, moderate entry barriers result in new players with rise of Automotive LiBs

Market entry barriers for battery materials

Market entry barriers	Cathode	Anode	Separator	Electrolyte
Investment need	◑	●	◑	○ 1)
Product know-how	◑	◑	●	●
Production know-how	◑	●	●	◑
Customer relationship	●	◑	◑	◑
Access to raw materials 2)	●	◑	○	○
New entrants (recent examples)	> BASF > Sumitomo Chem.	> Timcal	> Mitsubishi Chem. > Mitsui Mining > Idemitsu Kosan	> Idemitsu Kosan > Central Glass

● Very high ◑ Medium ○ Low

1) High for $LiPF_6$ (precursor material) 2) Access to mining capacities (esp. Ni, Co, Mn)

Source: Roland Berger "Battery material cost study V.2.4 / Q1 2011"

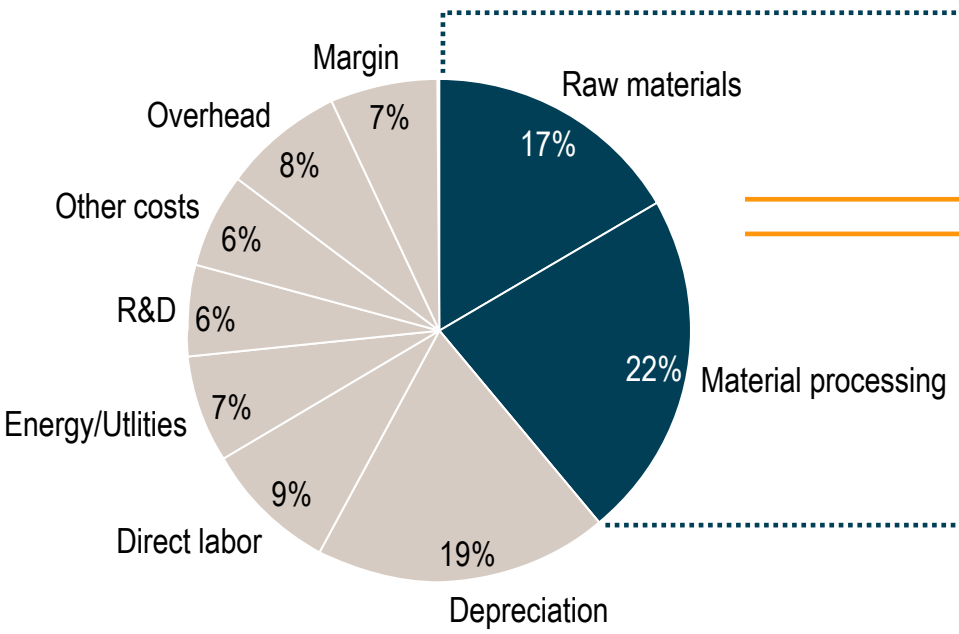
Roland Berger Strategy Consultants

The four analyzed materials account for 75% of cell material costs – Overall approx. 30% of today's total cell cost

Importance of different materials in cell battery cost structure

Battery cell cost breakdown, 2010[1)]

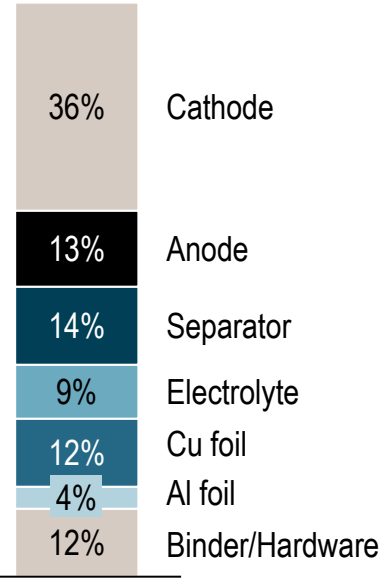
Total cost: approx. USD 500/kWh



Material cost split, 2010[1)]

~USD 195/kWh

~75%
(approx. 30% of total cell costs)



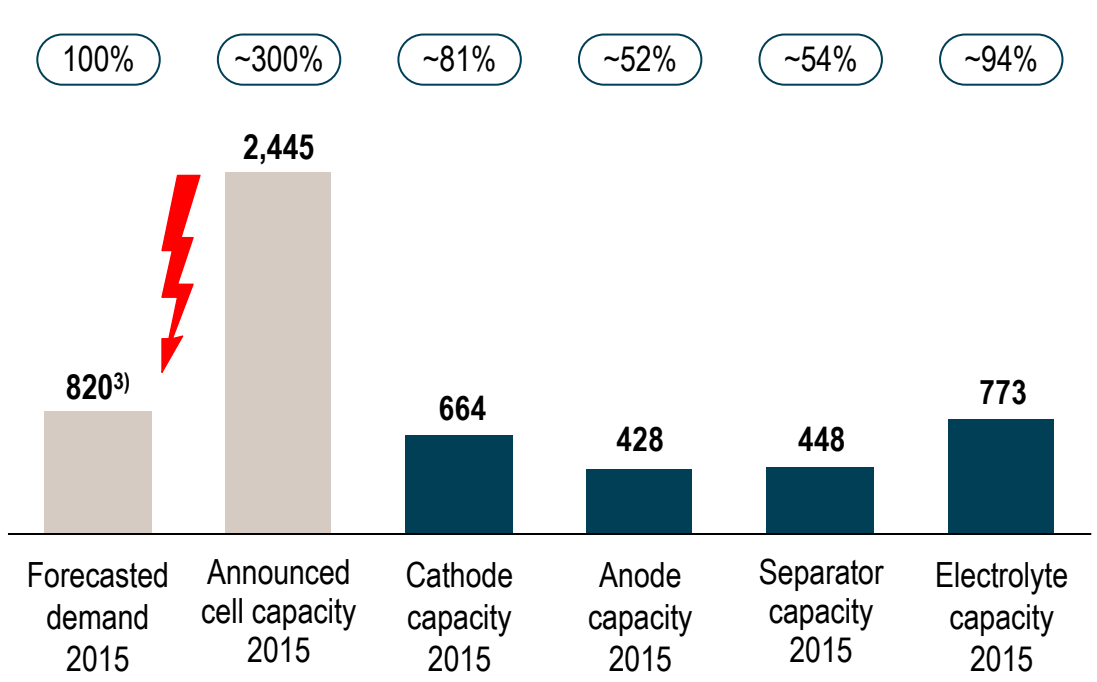
1) Approximate values for ternary mixture (NMC), depend on the chemistry and quality, excl. module/pack components (connectors, housing, BMS, cooling module)

Source: Roland Berger "Battery material cost study V.2.4 / Q1 2011"

Roland Berger Strategy Consultants

For materials, price pressure through overcapacities is not expected, as announced capacity build-up is below forecasted demand

Overview demand vs. cell capacity vs. material capacity[1)2)]



1) In '000 EV equivalents, 1 EV equivalent 20 kWh, for other assumptions please refer to p. 13
2) Capacity projections include announced plans by manufacturers, might not be exhaustive
3) RB high scenario "The future drives electric"
4) In % of forecasted demand from automotive

COMMENTS

> Li-Ion automotive related materials **capacities are lacking behind** the aggressive capacity increase of cell manufacturers, **especially anode** and **separator** materials

> Price reductions in materials therefore not expected to be driven by emerging overcapacities

> Demand from **consumer electronics** (~2.3 m EV equivalents in 2015) **not shown** on this chart

Source: Roland Berger "Battery material cost study V.2.4 / Q1 2011"

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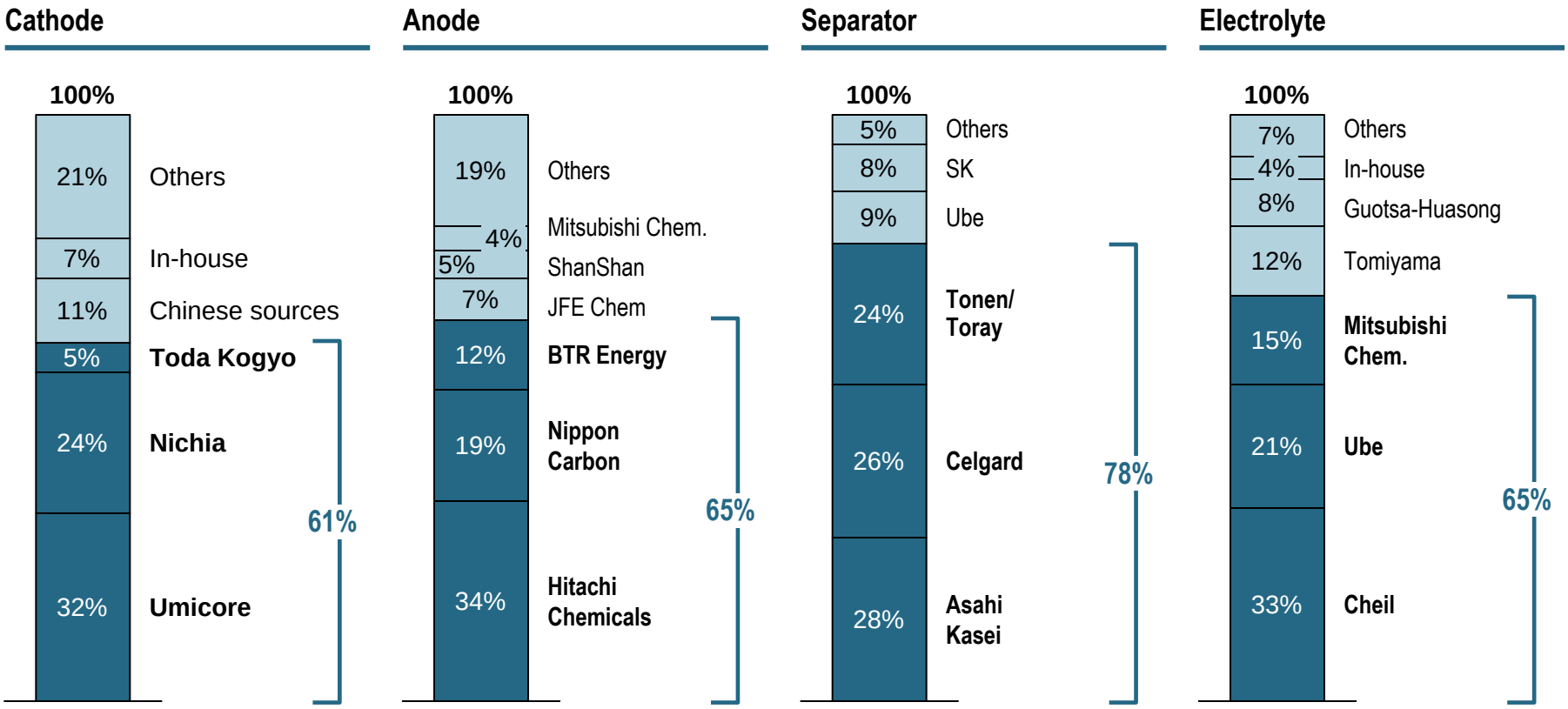
The market for the battery material is highly concentrated – Top-3 companies with 60-80% of the market

Market shares in Li-Ion battery raw materials, 2010 (all applications)



Source: IIT; Roland Berger analysis

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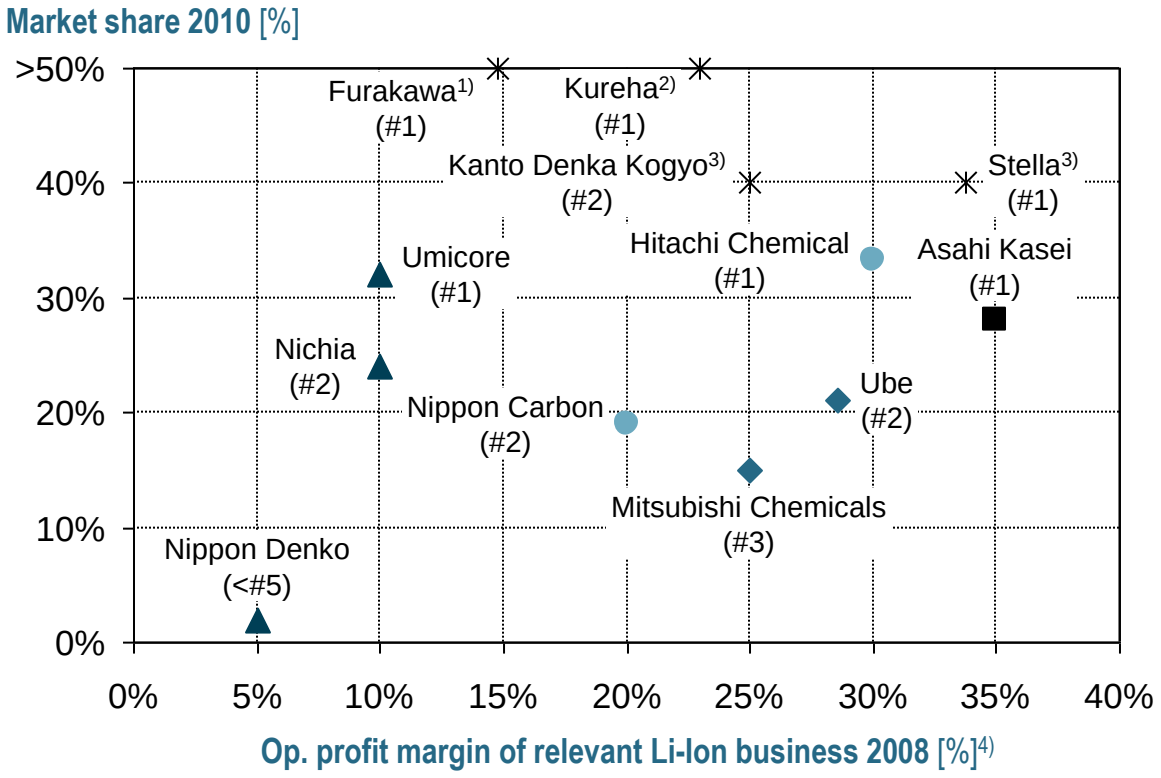
Scale is one of the major profit drivers in the market – Market leaders usually with highest profitability

Comparison market share vs. operating profit margin



COMMENTS

- Concentrated market leads to high operating margins due to economies of scale
- High market entry barriers exist for new players, especially for anode and separator material
- Average industry operating profit margins:
  - Cathode materials: 5-10%
  - Anode materials: 15-25%
  - Separators: 25-35%
  - Electrolyte solutions: 25-30%

● Anode materials ▲ Cathode materials ◆ Electrolyte solutions ■ Separators ✳ Other materials (pre- / by-products)

1) Aluminium foil 2) Binders 3) $LiFP_6$ (electrolytes) 4) Margin estimates per product for 2010 not available

Source: Roland Berger "Battery material cost study V.2.4 / Q1 2011"

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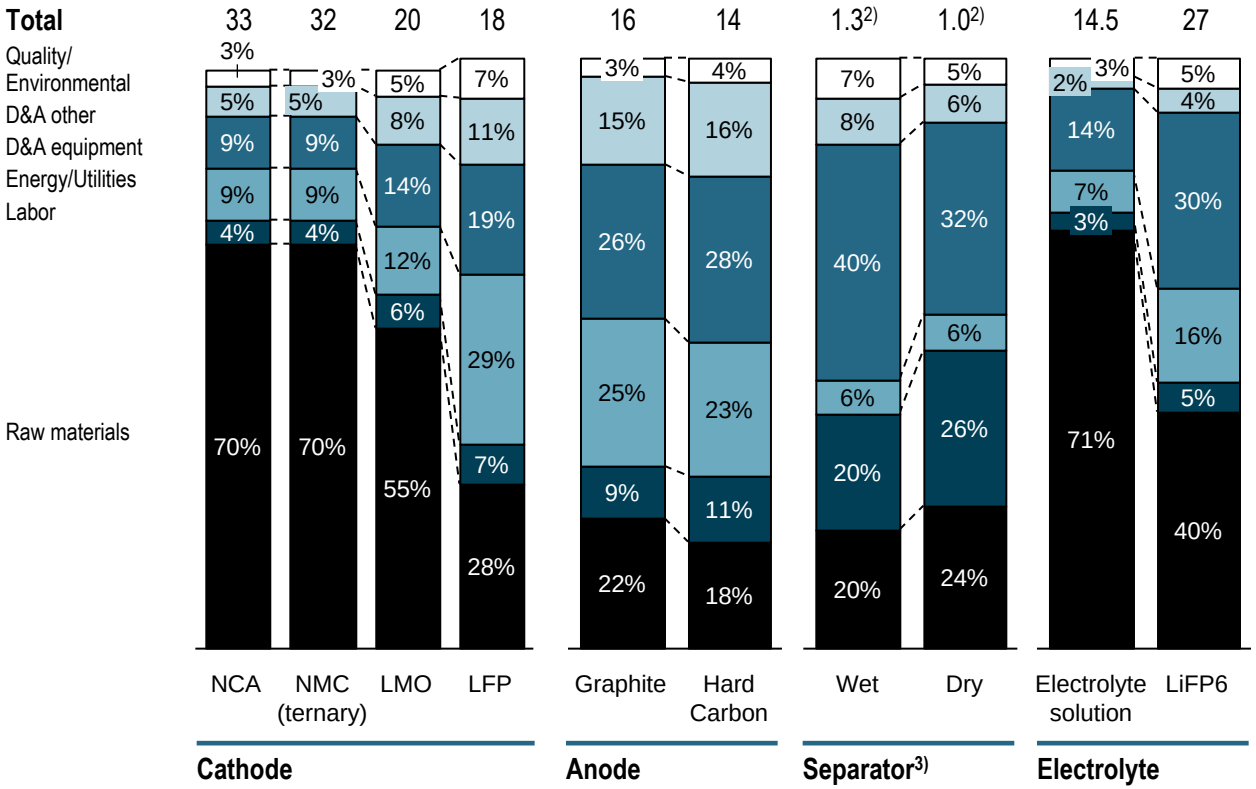
The cost structure of different materials reflects the know-how areas and major focus areas for cost reduction

Cost structure of different materials (2010)[1] [USD/kg]

Updated



COMMENTS

- Calculations based on following assumptions:
  - Full capacity utilization
  - Labor cost 100 k USD/year
  - Energy cost 5 US cent/kWh
  - Depreciation equipment 7 years
  - Land, building 10 years
- Costs are based on production in US (labor costs, energy costs per kWh, environmental costs etc.)
- R&D and overhead costs are excluded

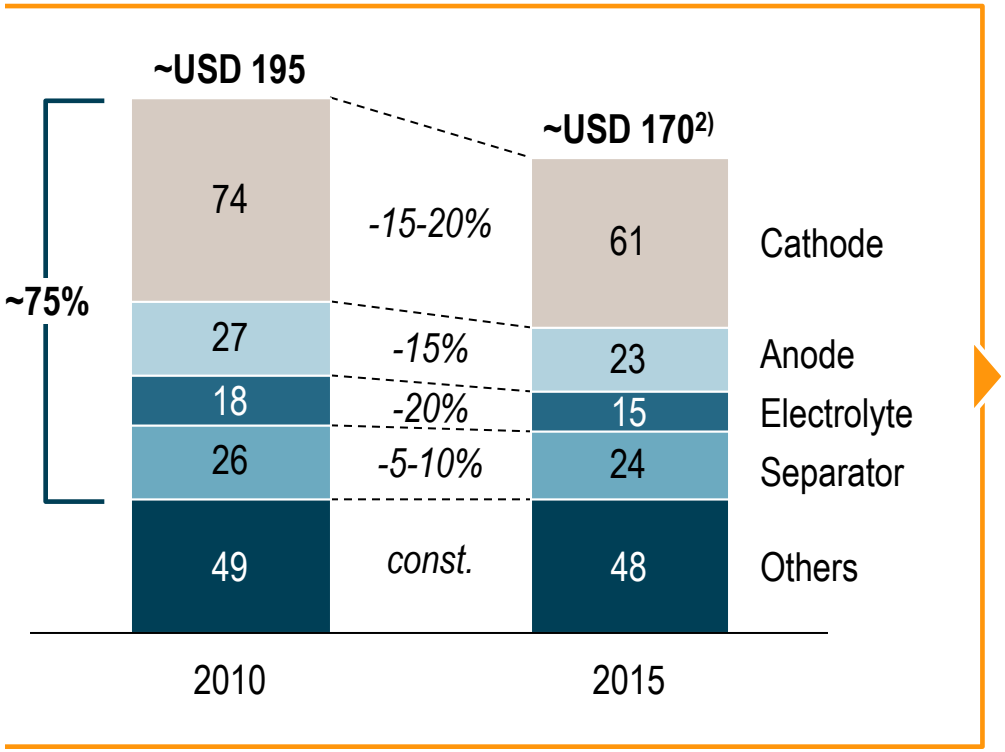
1) For typical battery grade materials, excludes R&D and overhead costs 2) In USD per m^2 3) Raw material cost in separators include subcontracting

Source: Roland Berger analysis

Roland Berger Strategy Consultants

Overall, the material prices are expected to fall by 10%..15% in the medium-term (without changes in composition or energy density)

Expected medium-term (2014/15) material price[1] development, estimates [USD/kWh]



- Largest contribution to the cost reduction from
  - Cathode due to decreasing raw material prices (Co, Ni) and intense competition
  - Anode due to commoditization
  - Electrolyte due to increasing competition (decreasing margins)
- Calculation assumes usage of same technologies and material compositions, and other material costs staying constant (binder, Cu/Al collector, housing)
- Further positive impact on the cell cost expected through new materials, increasing density of the materials

1) Approximate values for NCM cathode (ternary mix) and natural graphite anode , excludes potential improvements in production processes (investments as in 2010)
2) Overall, approx. 15% price decrease expected (incl.others/cell hardware)

Source: Roland Berger "Battery material cost study V.2.4 / Q1 2011"

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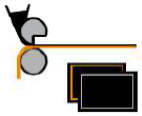
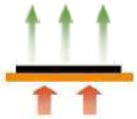
Cell manufacturing can be roughly divided into electrode manufacturing, assembly and electrical formation

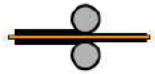
Production steps – Cell manufacturing

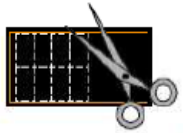
ELECTRODE MANUFACTURING


Slurry mixing


Coating


Evaporating


Compressing


Slitting

ASSEMBLY


Drying


Tab welding


Stacking


Packaging


Filling

ELECTRICAL FORMATION (SYSTEM DEPENDENT)


Formation

Final Storage and Testing

Source: M+W; Roland Berger

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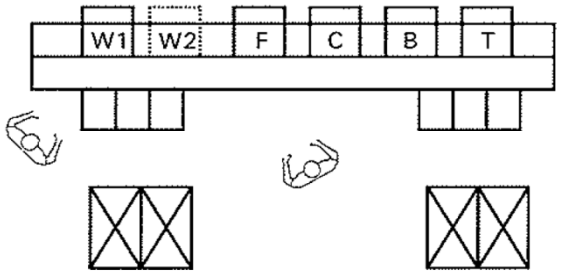
High automated manufacturing state of the art today – Low automated process only needs approx. 1/3 of total investment

Typical investments for cell capacity – High vs. low automation [USD/kWh][1)]

High automated manufacturing process

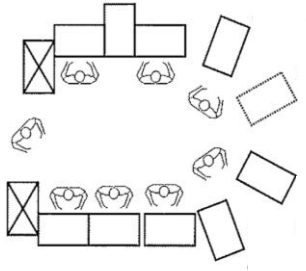
> State of the art due to high quality standards in the automotive industry



Invest approx. 300 USD/kWh

Low automated manufacturing process

> Only applied in low cost countries
> Significant cost saving potential, but high variations in product quality
> Equipment approx. 30-50% cheaper (low-cost sourcing, lower automation)



Invest approx. 100 USD/kWh

1) Production capacity of 100,000 batteries p.a. @20kWh capacity

Source: Roland Berger "LIB value chain cost model"

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For battery pack assembly, semi-automated processes assumed in Western countries – Approx. 2.5 times more investment required

Investments for battery assembly process [USD/kWh][1)]

- 4 assembly lines: cell to modules (incl. wiring and controller for cells and module)
- 2 lines: modules to packs
- Total

SEMI-AUTOMATED PROCESS	LOW-AUTOMATED PROCESS
20	8
10	4
~30	12
Likely to be applied in developed countries	State of the art in China

1) Production capacity of 100,000 batteries p.a. @20kWh capacity

Source: Roland Berger "LIB value chain cost model"

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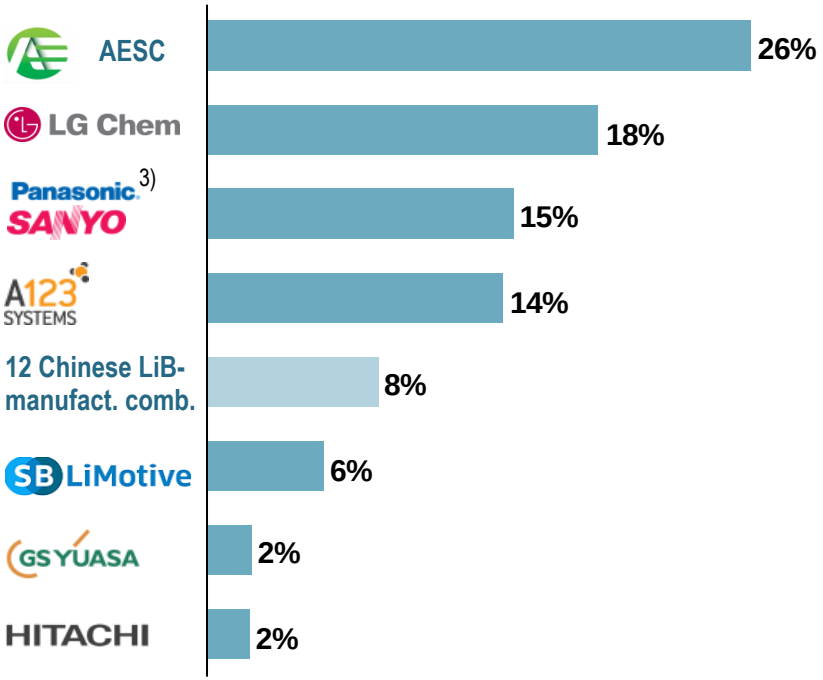
In 2015, five suppliers will have more than 80% of the LiB market – Chinese small in average, but account together for 8%

Key industry participants in 2015 (Passenger cars and CV)

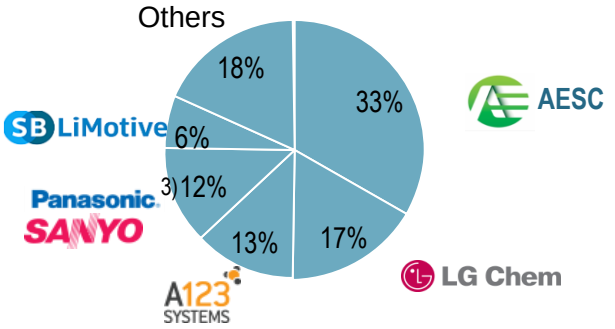
Expected 2015 global market share[1] [USD based[2]]

∑ = USD 8.9 bn

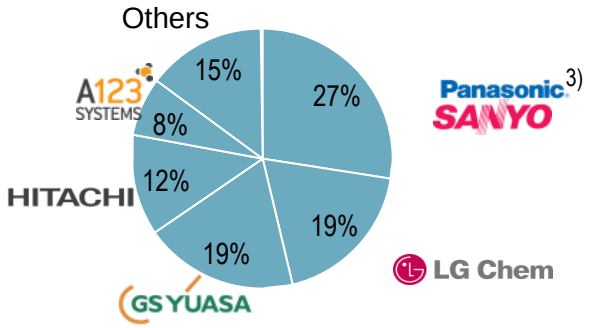


Expected 2015 global market share[1] [kW, kWh based]

PHEV and EV [kWh]



HEV [kW]



1) Accuracy level: +/- 2%; 2) Market value derived using USD 730/kWh for hybrids, USD 560/kWh for PHEV, and USD 400/kWh for EV in 2015; 3) Includes Primearth's share

Source: Roland Berger LiB market model Summer 2011

OEM-Supplier relationships are key inputs to determining market share

Key OEM customers by battery supplier

Battery supplier	OEM customer (contract/development)
A123 SYSTEMS 3)	BMW, DAIMLER, Hyundai, GM, NAVISTAR, BAIC, SMITH, VOLVO, McLaren AUTOMOTIVE 2), TATA 2), VIA 2), BRIGHT AUTOMOTIVE 2)
GS YUASA	HONDA, MITSUBISHI, PSA PEUGEOT CITROËN
HITACHI	GM, ISUZU, PACCAR, DAIMLER, NAVISTAR, FUSO, SUBARU 2)
Johnson Controls, SAFT 1)	BMW, DAIMLER, Ford, GAC GROUP, ODYNE, COLLINS BUS CORPORATION, TATA 2), FIAT 2), 2)
LG Chem	GM, HYUNDAI, Ford, RENAULT, VOLVO, NAVISTAR, PACCAR, IVECO, DAIMLER 2), DAEWOO 2)
AESC	NISSAN, RENAULT
Primearth EV Energy Co., Ltd, Panasonic, SANYO	TOYOTA, Ford, VOLKSWAGEN AKTIENGESELLSCHAFT, SUZUKI, mazda, SUBARU, SCANIA, DAIMLER 2), ASTON MARTIN 2)
SB LiMotive	BMW, FIAT, PSA PEUGEOT CITROËN 2), VOLKSWAGEN AKTIENGESELLSCHAFT, DAIMLER, NAVISTAR 2)

1) Before dissolution, assumes Ford, Daimler, BMW discontinue relationship at end of current programs; 2) Minor relationship; 3) also includes many bus relationships

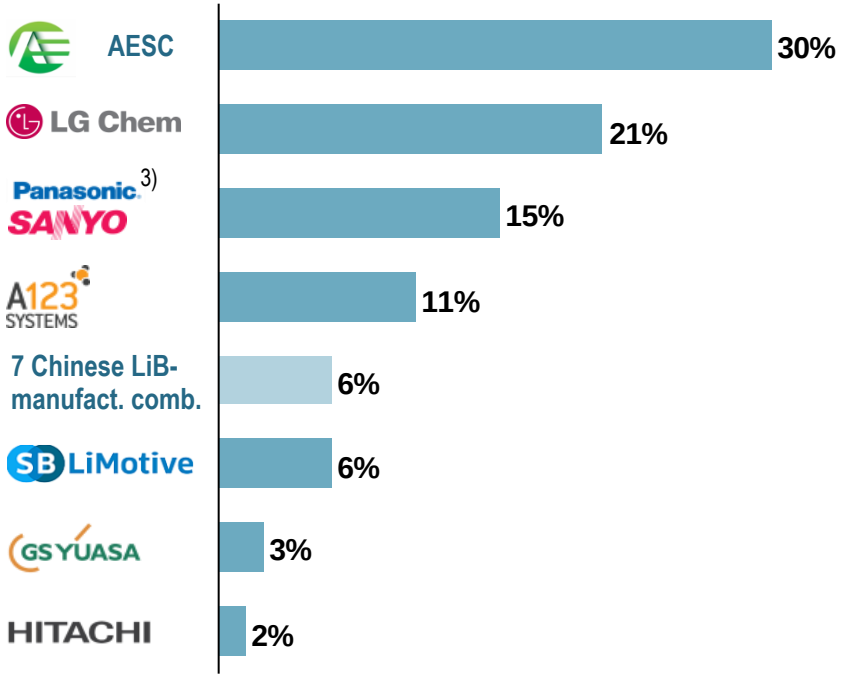
Source: Roland Berger LiB market model Summer 2011

In light vehicles, typically 2 suppliers are selected strategic partners – share as "2nd source" could change market share by +/- 2%

Key industry participants in 2015 (Light vehicles)

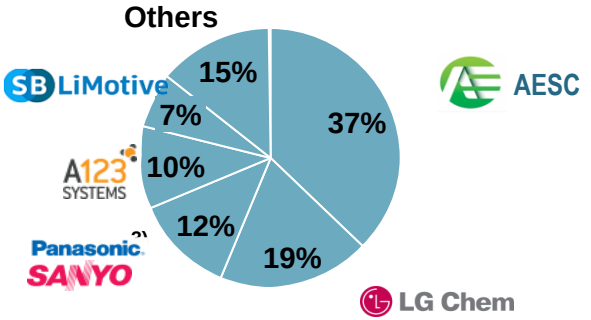
Expected 2015 global market share[1] [USD based[2]]

∑ = USD 7.6 bn

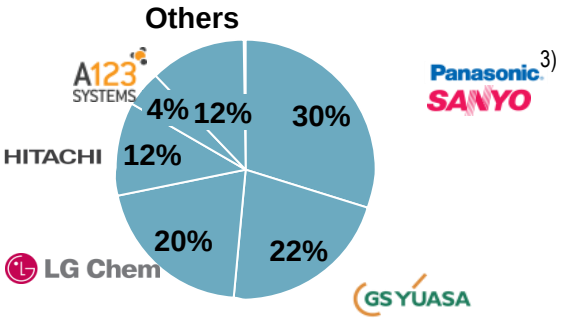


Expected 2015 global market share[1] [kW, kWh based]

PHEV and EV [kWh]



HEV [kW]



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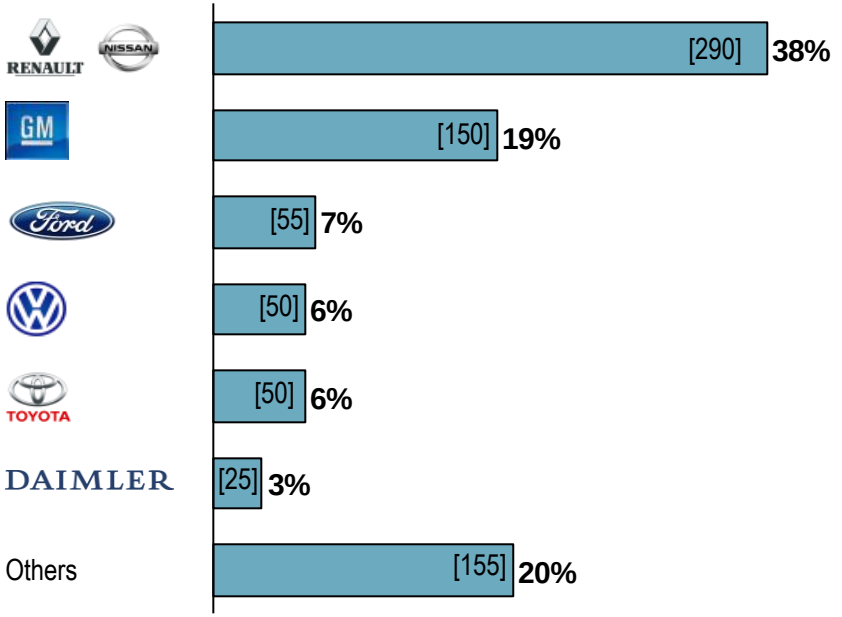
Source: Roland Berger LiB market model Summer 2011

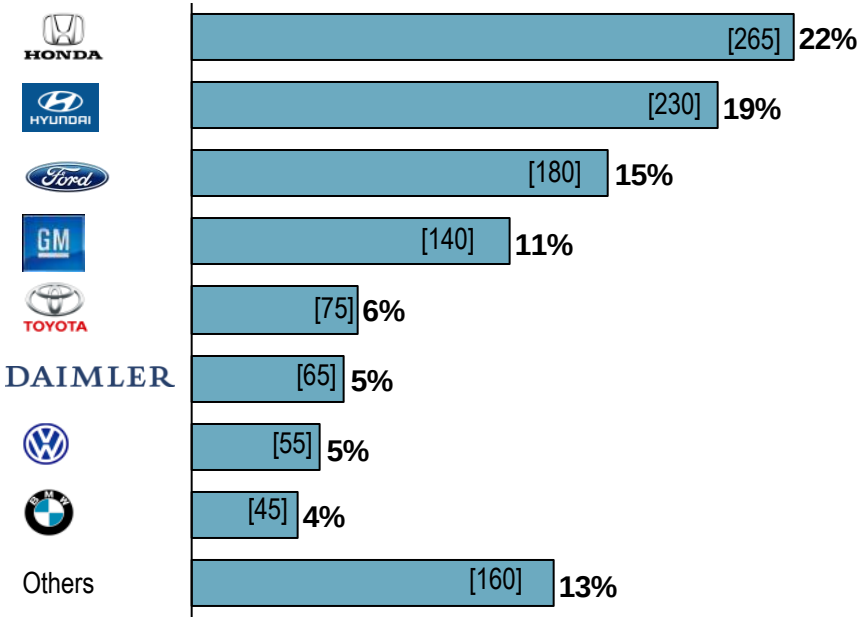
The market shares in light vehicles are heavily dependent on key OEMs meeting their xEV production targets

2015 expected light vehicle OEM xEV production and share (LiB only)

2015 expected OEM production and share – PHEV/EV[1)]



2015 expected OEM production and share – HEV[1)]



[xx] 2015 forecasted production volume ['000s]

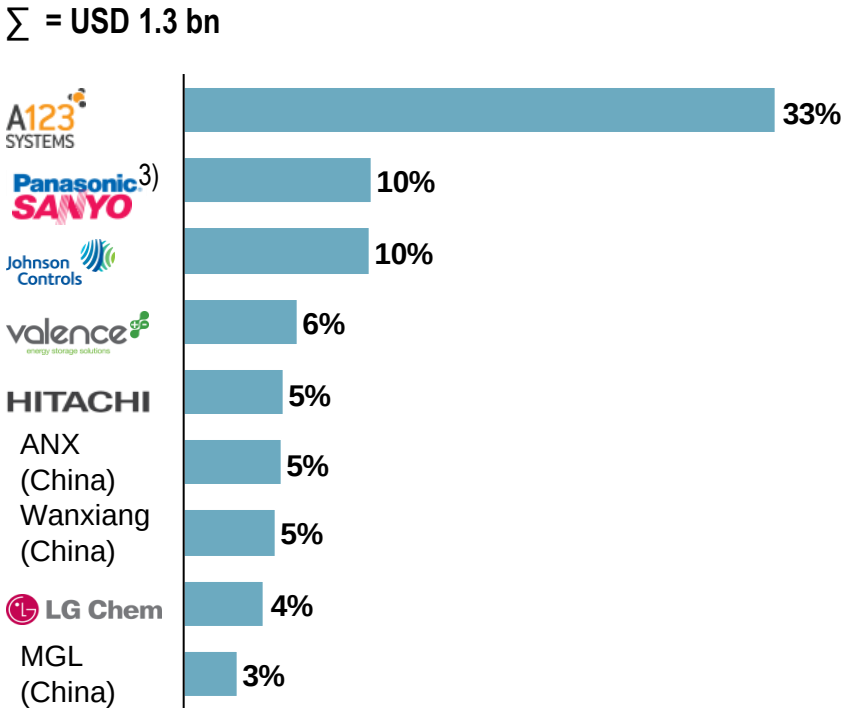
1) Share and forecasts are for vehicles with Li Ion batteries

Source: Roland Berger LiB market model Summer 2011

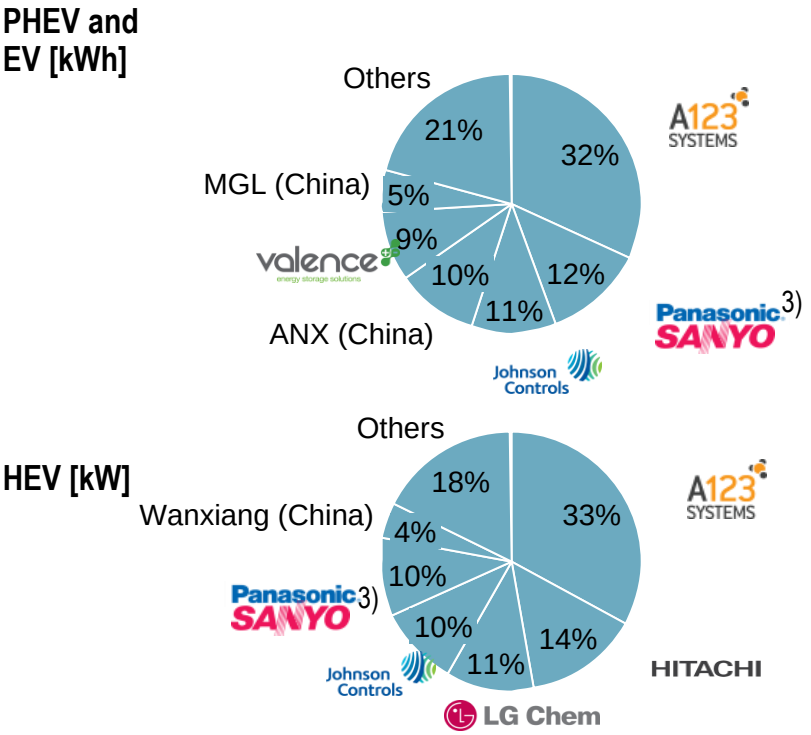
In trucks and buses, Chinese players have a more important role due to high demand for buses and usage of LiFePo4

Key industry participants in 2015 (Trucks and buses)

Expected 2015 global market share[1] [USD based[2]]



Expected 2015 global market share[1] [kW, kWh based]



1) Accuracy level: +/- 2%; 2) Market value derived using USD 730/kWh for hybrids, USD 560/kWh for PHEV, and USD 400/kWh for EV in 2015; 3) Includes Primearth's share

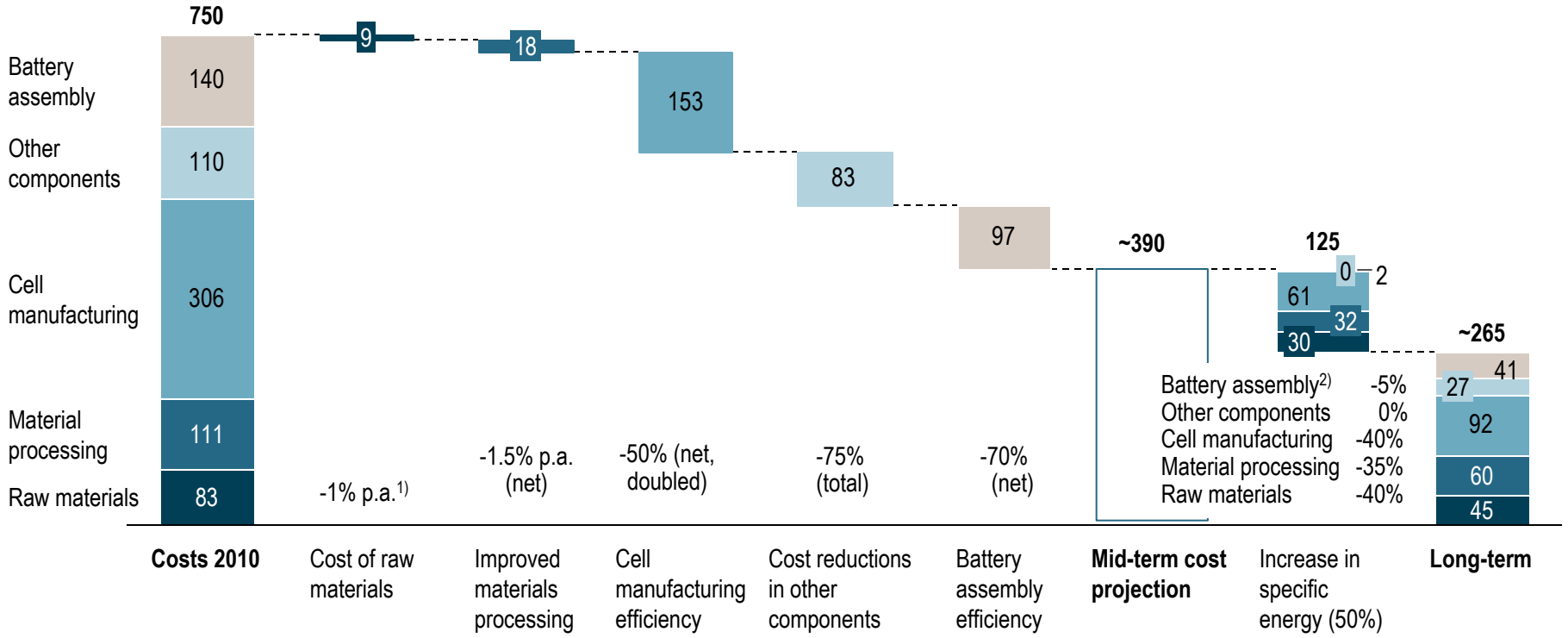
Source: Roland Berger LiB market model Summer 2011

Roland Berger Strategy Consultants

Increase in specific energy and in cell manufacturing efficiency will drive down costs to below 265$/kWh on pack level

Necessary increase of energy density – Ternary mix (NMC) – Cost projection

COST REDUCTION LEVERS FOR BATTERY PRODUCTION [USD/kWh]

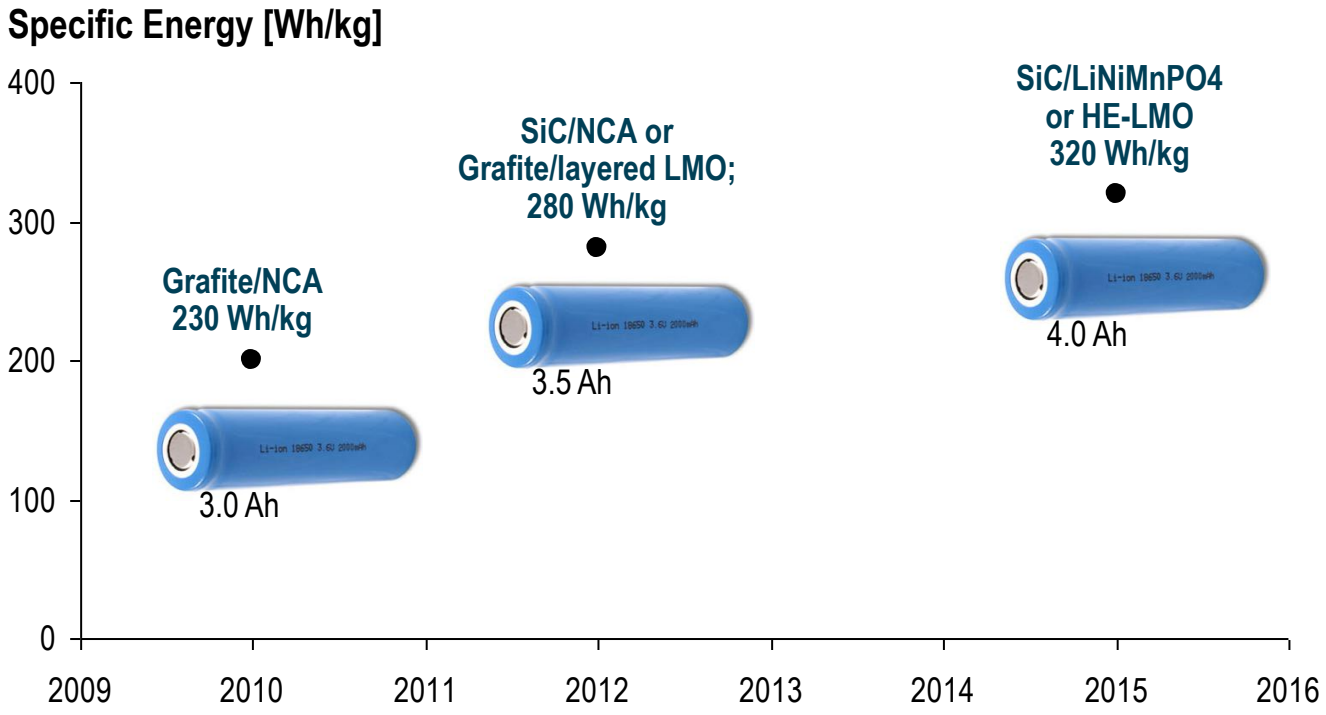


1) Mainly driven by decrease of cathode material costs (Co, Ni) 2) Battery management system, housing, etc.

Source: Roland Berger "LIB value chain cost model"

Li-Ion battery still have significant potential in energy density increase – High technology dynamic to be expected

Li-Ion consumer cell development roadmap



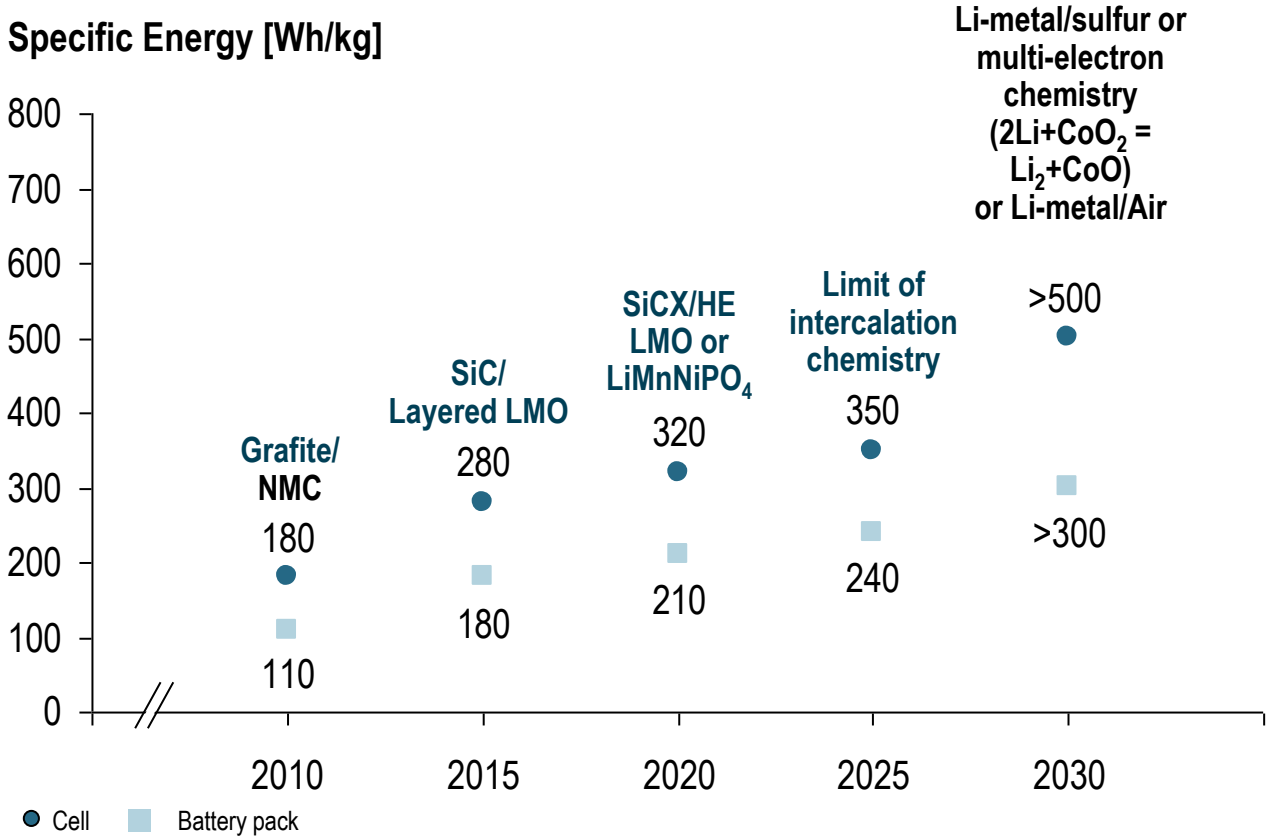
- Nano structured materials based on silicon and silicon composites for the anode
- High voltage and high energy layered oxides and/or high voltage phosphates for the cathode
- Automotive cell development will greatly benefit form consumer with a 3 to 5 year delay!

Source: Roland Berger analysis

Roland Berger Strategy Consultants

We expect that in 2025 a specific energy of 240 Wh/kg on pack level could be reached

Large format Li-Ion-battery development roadmap



- The **Li-Ion chemistry** will **dominate** the consumer and automotive markets **for a very long time** due to their high efficiency, long cycle and calendar life, high energy density and manageable safety
- **Further increase** in energy density is possible **with lithium metal systems**, but **intrinsic problems** with reversibility, cyclability and safety of lithium metal need to be overcome to make lithium metal based systems viable

Source: Roland Berger analysis

Other emerging technologies beyond Lithium-Ion still face significant issues - break-through not foreseeable in next 10..15 years

Battery System	Main Advantages	Disadvantages	Probability of success for EV/PHEV/HEV (%)
Li-metal/Sulfur	Low cost	Low cycle life, safety issues	<50%
Li-metal/Air	Low cost	Low cycle life, low efficiency, safety issues	<30%
Li-Ion/Flow battery (Cambridge Crude)	Separation of energy storage from energy conversion	Pumping of liquids containing dispersed nano particles	Unclear
Li/metal polymer (60 °C)	No liquids	Heating required, low power output, safety issues	<50%
Li-metal/Multi-electron chemistry	High energy density	Low cycle life, low efficiency safety issues	<50%
Sodium/Sulfur (Na/S)	Good cycle life, low cost	Works at 300° C	For large vehicles in fleet applications only
Sodium/Nickel chloride (ZEBRA)	Good cycle life, reasonable cost	Works at 350° C	For large vehicles in fleet applications only
Redox flow batteries	Low cost	Low power output, pumping of liquids	<10%
Sodium and Magnesium ion batteries	Low cost	Low reversibility, low power output	<20%

Source: Roland Berger analysis

The value chain is expected to consolidate and to develop a clearer tiered structure (1/2)

	TODAY (2010)	CHANGES BY 2020
Raw materials Lithium mining	> Oligopoly	> Some selected new players > New **recycling** companies > Business models integrating recycling
Anodes, Cathodes, Separators, Electrolytes and Precursors	> Dominated by Asian (Jap.) players > Partially specialized precursors sourced > Some cathode materials manufactured by cell manufacturer	> **New players** (from specialty chemical sector) especially for Automotive and Solar > More **integration of precursor** manufacturer > Cathode manufacturing by cell manufacturer only for top 2..3 with large chemical business

Source: Roland Berger

The value chain is expected to consolidate and to develop a clearer tiered structure (2/2)

	TODAY (2010)	CHANGES BY 2020
Battery cells / stacks ("LiB manuf.")	> New JVs (Auto-Consumer LiB manuf.) > Indepen. Asian LiB > Research spin-offs with public & IPO funding	> Massive **consolidation** (cost pressure, innovation) > Less upstream integration (esp. cathode/anode material) > More downstream integration, **cell manufacturer as Tier-1s** to OEMs > Auto-Cell manuf. **JV's as exemption**
Battery assembly	> Mainly by OEMs (JVs LiB) inhouse > Selected supplier – LiB JVs > Limited LiB alone	> Increased **outsourcing**, but still **dominated** by **in-house assembly** > Cell manufacturers will deliver larger part of system (incl. electronics) as Tier-1

Source: Roland Berger

Agenda

A **MARKET DEVELOPMENT:**
We expect that by 2020 xEVs sales volume can capture up to 8% .. 10% of global sales, provided battery costs come down

B **CURRENT VALUE CHAIN:**
Cell manufacturing and processing of active materials represent major parts of current costs – value chain today dominated by Asian players

C **BATTERY COST AND VALUE CHAIN DEVELOPMENT:**
With battery costs decreasing down to 250 USD/kWh in 2020, the value chain is expected to consolidate and to develop a clearer tiered structure

D **IMPLICATIONS:**
The Li-Ion-battery value chain will change dramatically, automotive companies need to reflect these dynamics in products, partnering strategies and processes

Roland Berger Strategy Consultants

The Li-Ion-battery value chain will change dramatically during this decade

> **Cell costs decreasing rapidly:**
process and manufacturing technology improvements, improved materials, new competitors

> **Shake-out of cell producers/consolidation of value chain:**
6..8 mostly Asian manufacturers likely to serve OEMs as Tier 1's (NEC/AESC, LG Chem, Panasonic/Sanyo, A123, SBlimotive, GSYuasa or Hitachi, likely one/two Chinese)

> **Li-Ion intercalation chemistries will dominate the market:**
high technology dynamics to be expected in the next decade

Source: Roland Berger

Roland Berger Strategy Consultants

Auto companies needs to reflect these dynamics in its products, partnering strategies and processes

Cell costs

Consolidation

Technology dynamics

IMPLICATIONS

> **"Upgradable" product architecture:**
Based on clearly defined interfaces regarding energy, information, cooling, packaging, upgradability control / operating strategies etc.

> **Strategically managed partnership process:**
Portfolio of partnerships with technology leaders, regular review and proactive alliance management required

> **Faster and dedicated product creation process for electric drive train:**
Ability to integrate and test new cell types in < 2 yrs. , based on upgradable product architecture

Source: Roland Berger

Contact details

Please contact us for further information

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