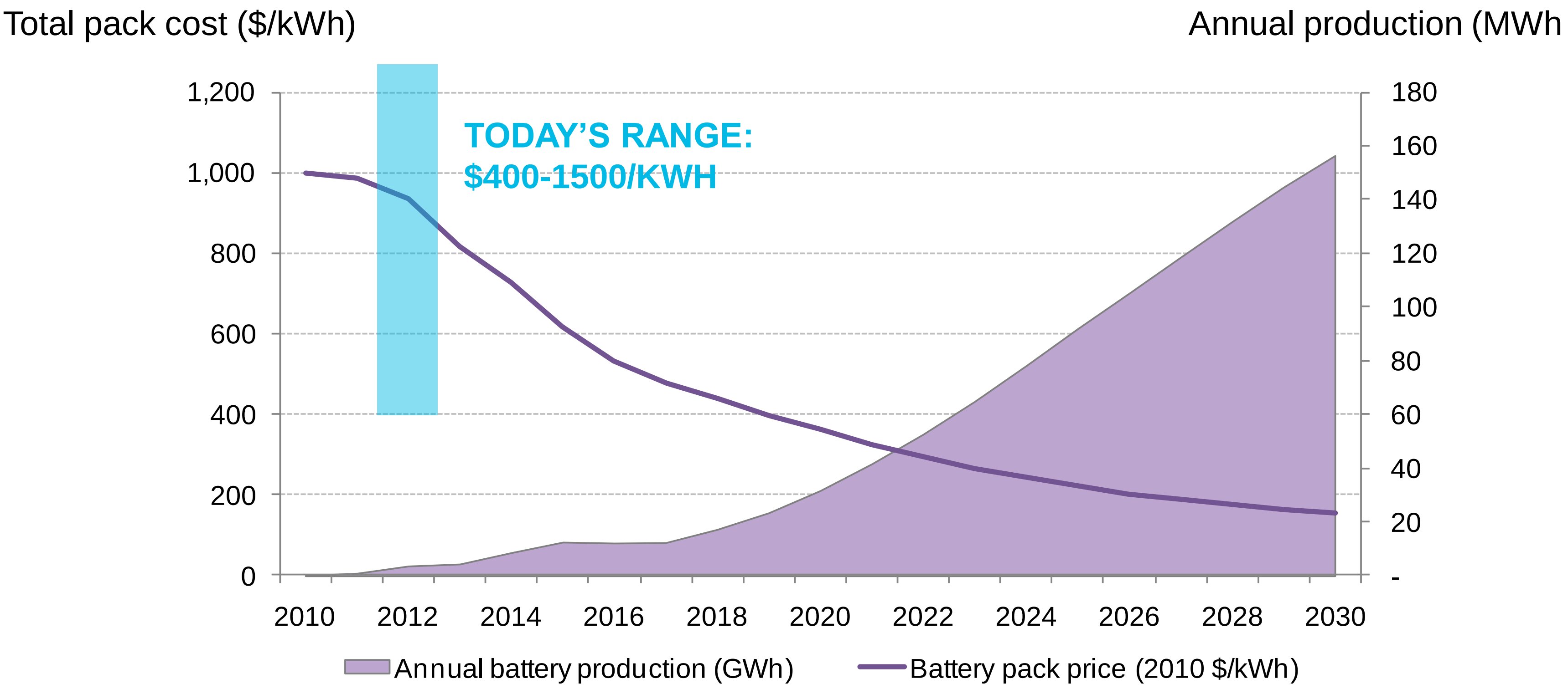
BATTERY INNOVATION: INCREMENTAL OR DISRUPTIVE?

ALBERT CHEUNG

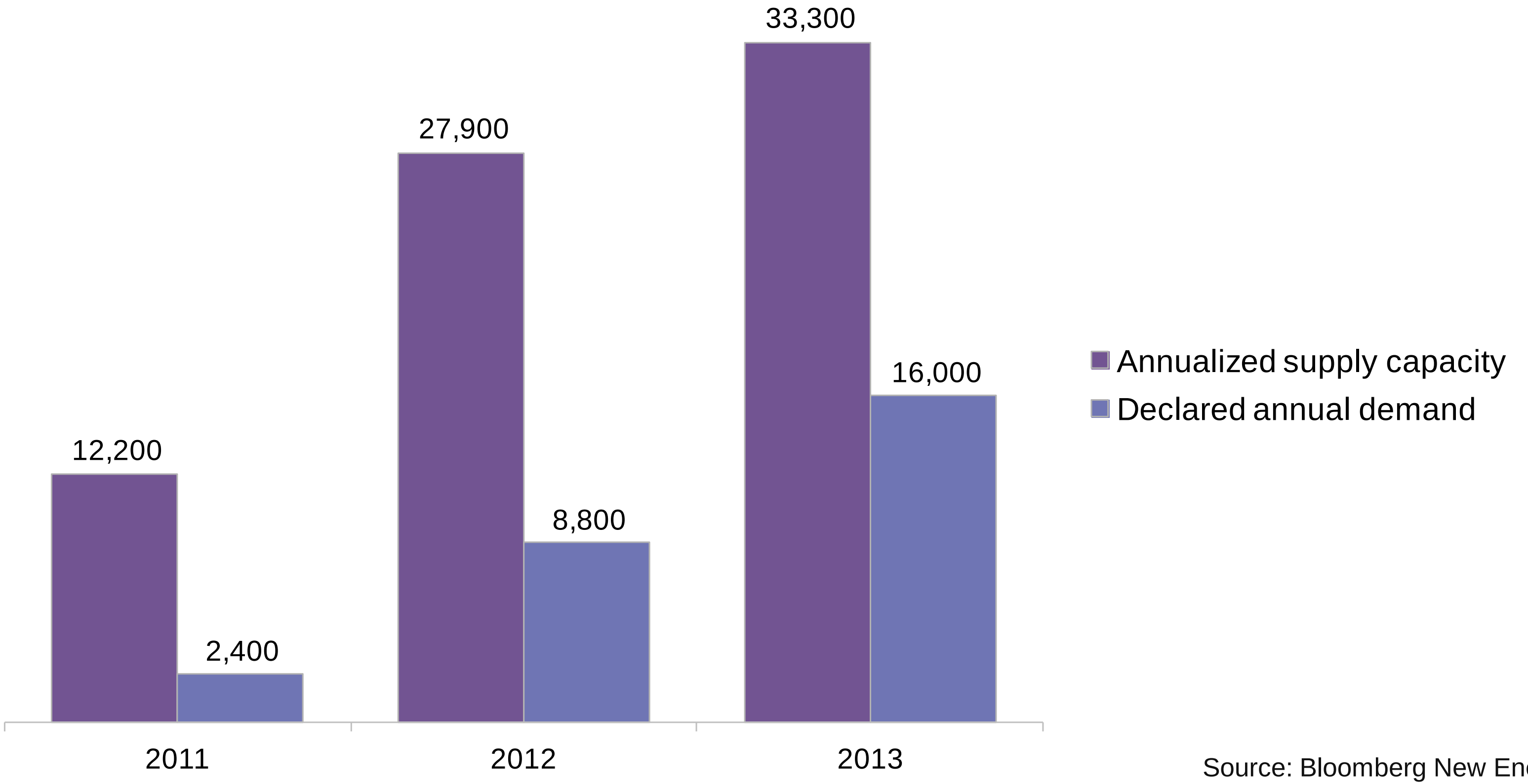
Bloomberg
NEW ENERGY FINANCE

LI-ION BATTERY PACK COST AND PRODUCTION, 2010-30



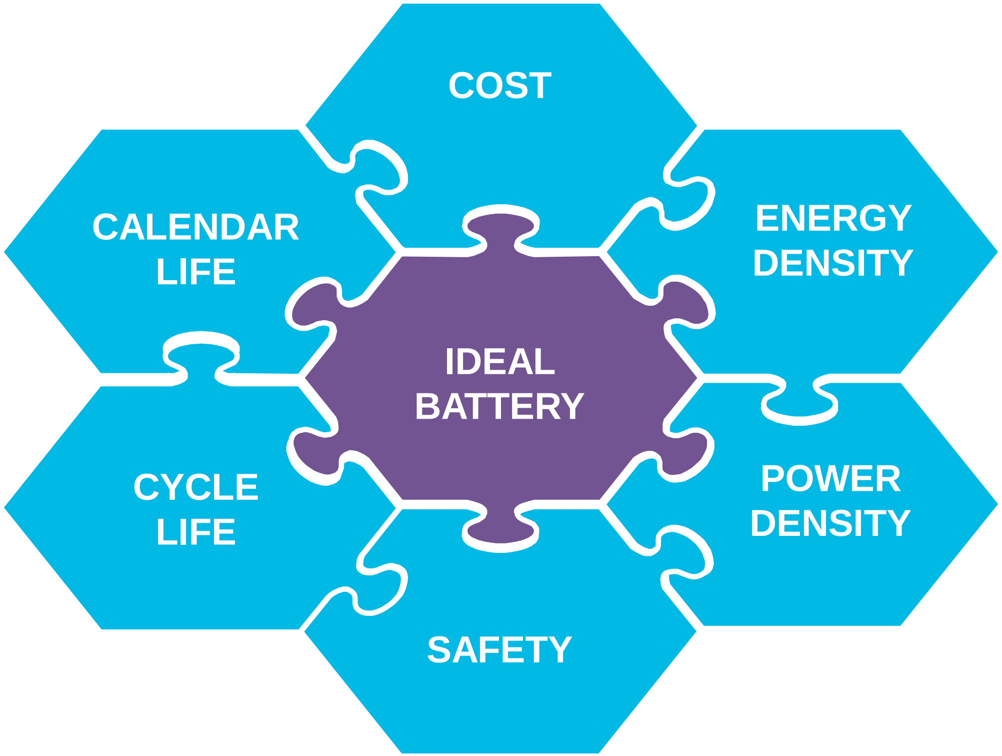
Source: Bloomberg New Energy Finance

EV LITHIUM ION BATTERY SUPPLY & DEMAND (MWH)



Source: Bloomberg New Energy Finance

COST IS JUST ONE OBJECTIVE



WHERE WILL GAINS BE MADE?

Raw/processed materials

↓

LFP, NCM, electrolytes, etc.

Battery materials

↓

Cells

↓

Packs

↓

Vehicle Integration

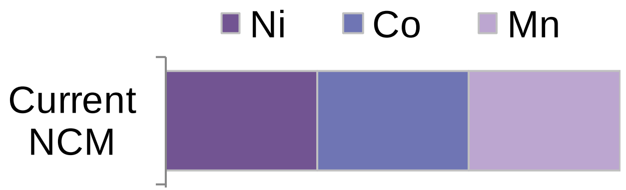
Cost | **Performance**

- Alternative electrodes / electrolytes
- Materials development
- Cell size and format
- Cell design features
- Pack design
- Pack assembly | Thermal management
- Chassis integration
- Integration with other vehicle systems

Process improvement & scale

‘INCREMENTAL’ IMPROVEMENT IN CATHODE CHEMISTRY

CATHODE COMPOSITION



NCM PROPERTIES

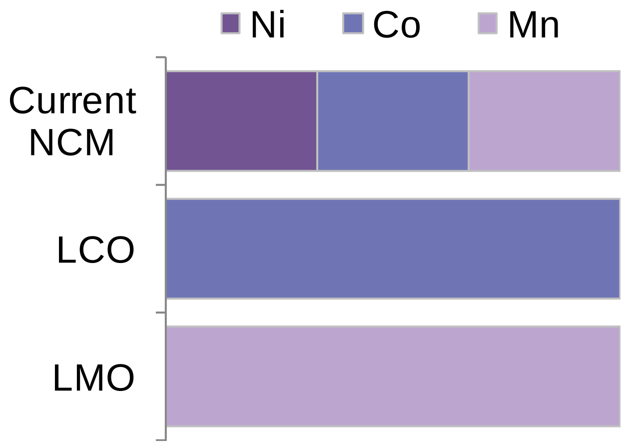
- NCM is one of several cathode types in use
- Blend of three lithium oxides: nickel / cobalt / manganese
- Major users include Sanyo (Panasonic) and GS Yuasa

- Good energy density
- Moderate safety (not as stable as LFP)

Source: Bloomberg New Energy Finance.

‘INCREMENTAL’ IMPROVEMENTS IN CATHODE CHEMISTRY

CATHODE COMPOSITION



LMO AND LCO PROPERTIES

LCO: lithium cobalt oxide

- Older technology (consumer batteries)
- Good energy density
- Poor safety / thermal properties

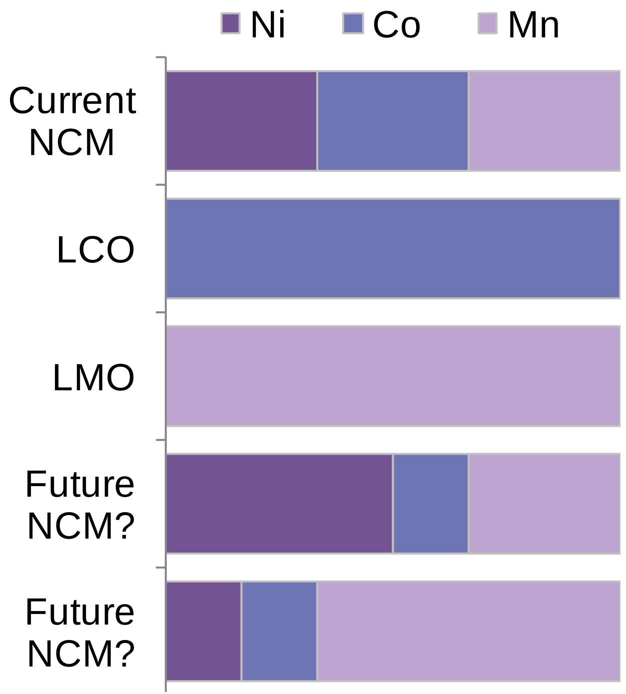
LMO: lithium manganese oxide

- Current technology (eg Nissan, GM, LG Chem)
- Good safety / thermal properties
- No expensive cobalt
- Lower energy density

Source: Bloomberg New Energy Finance.

‘INCREMENTAL’ IMPROVEMENTS IN CATHODE CHEMISTRY

CATHODE COMPOSITION



POSSIBLE FUTURE BLENDS OF NCM

Less cobalt?

- Lower cost
- Better safety / thermal properties
- Similar performance

More nickel?

- Increases energy density

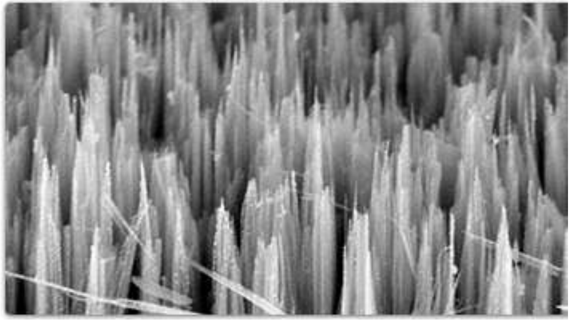
More manganese?

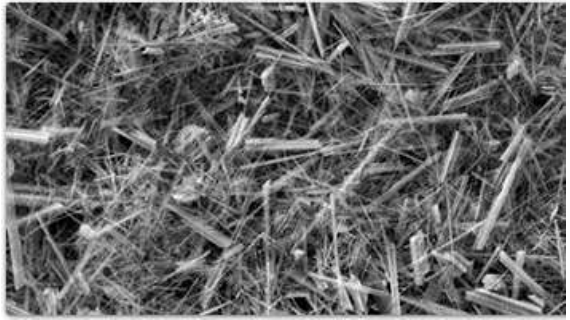
- Potentially much higher energy density and lower cost
- Needs better electrolytes and anode
- Very early stage

Source: Bloomberg New Energy Finance.

'DISRUPTIVE' CHANGE IN ANODE MATERIALS: SILICON

- Silicon theoretically absorbs 10x as many Li ions as graphite - much higher E density
- Historic problem: silicon structures suffer from fatigue/pulverisation after a few cycles
- Solution: nanostructures / nanowires





- Axeon claims energy density improvement of 35%, Panasonic claims 20%
- Panasonic and LG Chem aim to launch Si-anode consumer batteries in 2012-13
- Only small cell formats being commercialised

Source: Images from Nexeon.

‘DISRUPTIVE’ CHANGE IN ANODE MATERIALS: SILICON

Carbon anode:

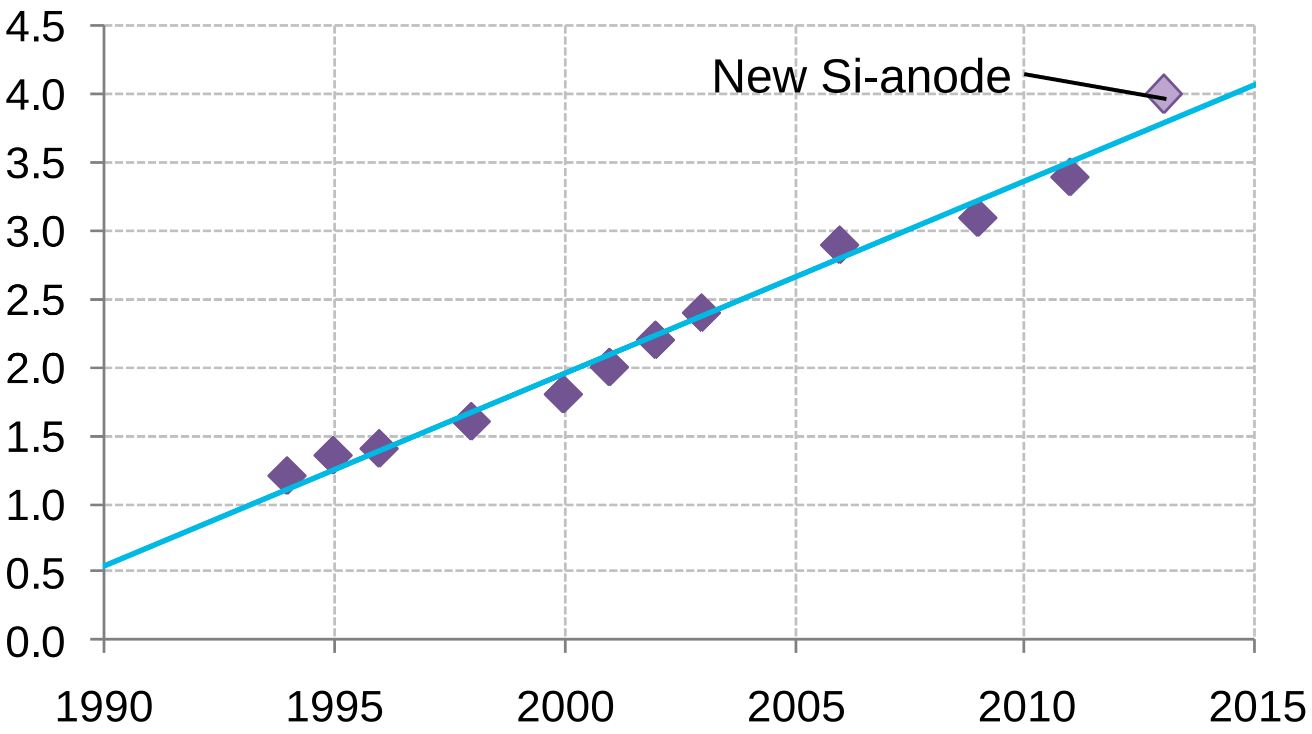
$$6C + Li^{+} + e^{-} \leftrightarrow LiC_6$$

Silicon anode:

$$4Si + 15Li^{+} + 15e^{-} \leftrightarrow Li_{15}Si_4$$

Source: Images from Nexeon.

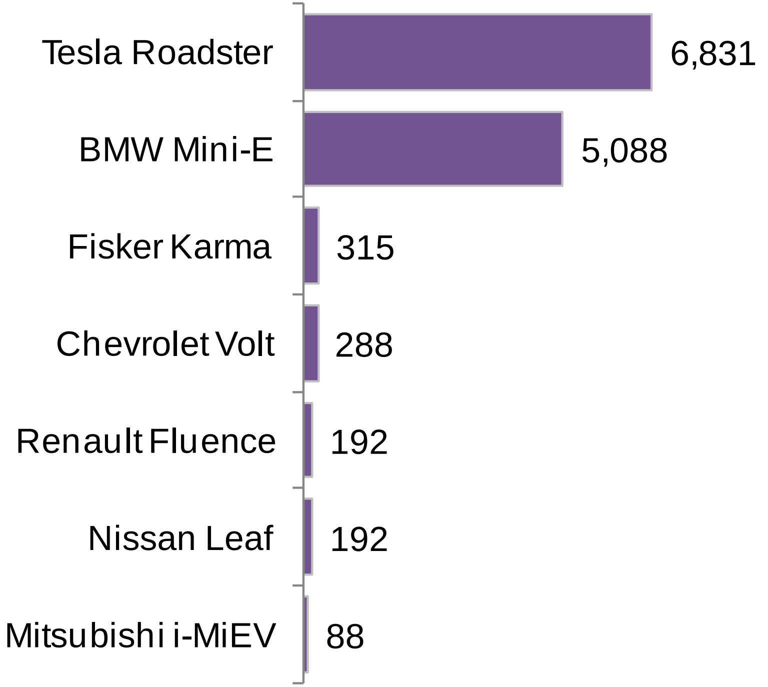
MAX CAPACITY OF 18650-FORMAT LI-ION CELLS (AH)



Source: Bloomberg New Energy Finance, Nikkei.

CELL AND PACK DESIGN CHOICES

NUMBER OF CELLS IN MAIN EV MODELS



CONSIDERATIONS

18,650 format (consumer cells, 2-3Ah):

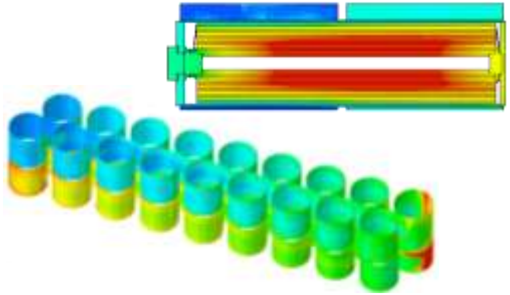
- Leverages decades of experience
- Sophisticated management system needed
- Not as applicable for PHEV

Larger cells (up to 50Ah):

- Easier packaging and thermal mgmt
- Greater potential for improvement with experience
- Second life considerations?

OTHER AREAS OF INNOVATION

THERMAL MANAGEMENT



- Air vs. liquid cooling
- Small vs. large cells
- Intra/inter-cell thermal gradients
- Use of CFD and advanced BMS

VEHICLE INTEGRATION

- Bespoke vehicle platforms
- Battery placing and design can impact:
    - Handling
    - Safety
    - Cost

Source: Images from Axeon.

CONCLUSIONS

- There will continue to be innovation at every step of the value chain
- There are no clear lines between ‘incremental’, ‘step-change’ and ‘disruptive’ innovation
- Innovation is non-linear and the experience curve hides many subtleties
- There will be winners and losers

- There are technologies that could ‘re-boot’ the experience curve: lithium-air, magnesium-ion, flow batteries, nanotube electrodes, etc...

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