CAPITAL MARKETS DAY

POWERING AHEAD

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materials for a better life

Seoul, Korea

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Innovation roadmap in clean mobility materials

SPEAKER

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Chief Technology Officer

Executive Vice-President Energy & Surface Technologies

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Agenda

Well to wheel efficiency considerations

Key developments in xEV battery materials

Key developments in fuel cells

Wrap-up

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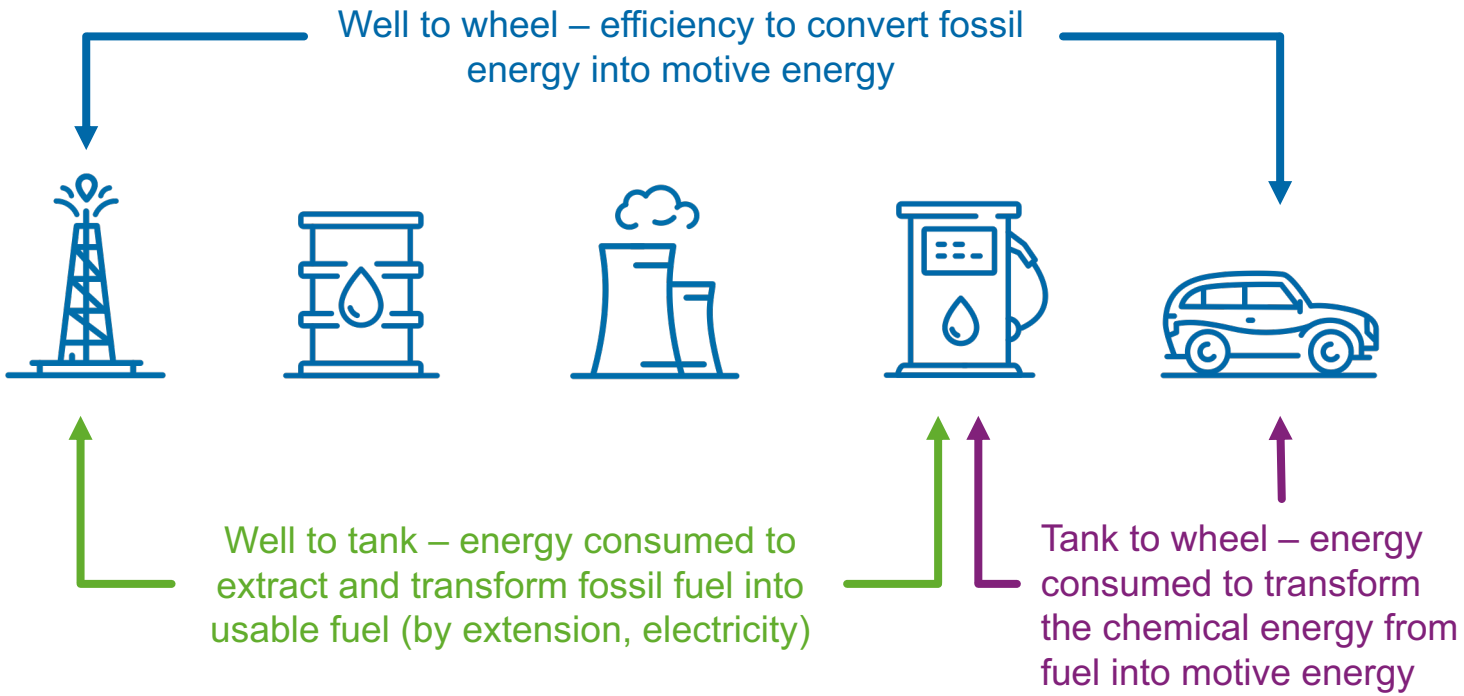
On the road towards clean mobility

Well to wheel efficiency considerations

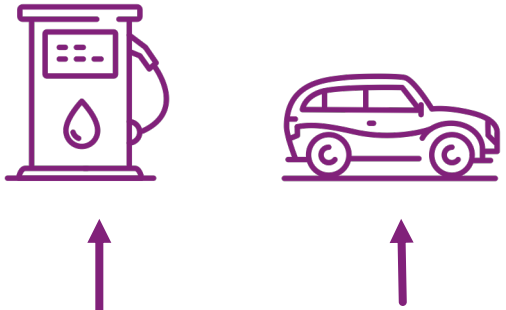


On the road towards clean mobility

There's nothing like BEV in terms of tank to wheel efficiency

ENERGY CONTENT (Wh/kg)	
Gasoline	**13,100**
Diesel	**12,700**
Hydrogen	**39,400**
Li-Ion battery	**280**

APPROXIMATE TTW PER DRIVETRAIN	
Gasoline	**25%**
Diesel	**30%**
FCEV	**50%**
BEV	**90%**



Tank to wheel – energy consumed to transform the chemical energy from fuel into motive energy

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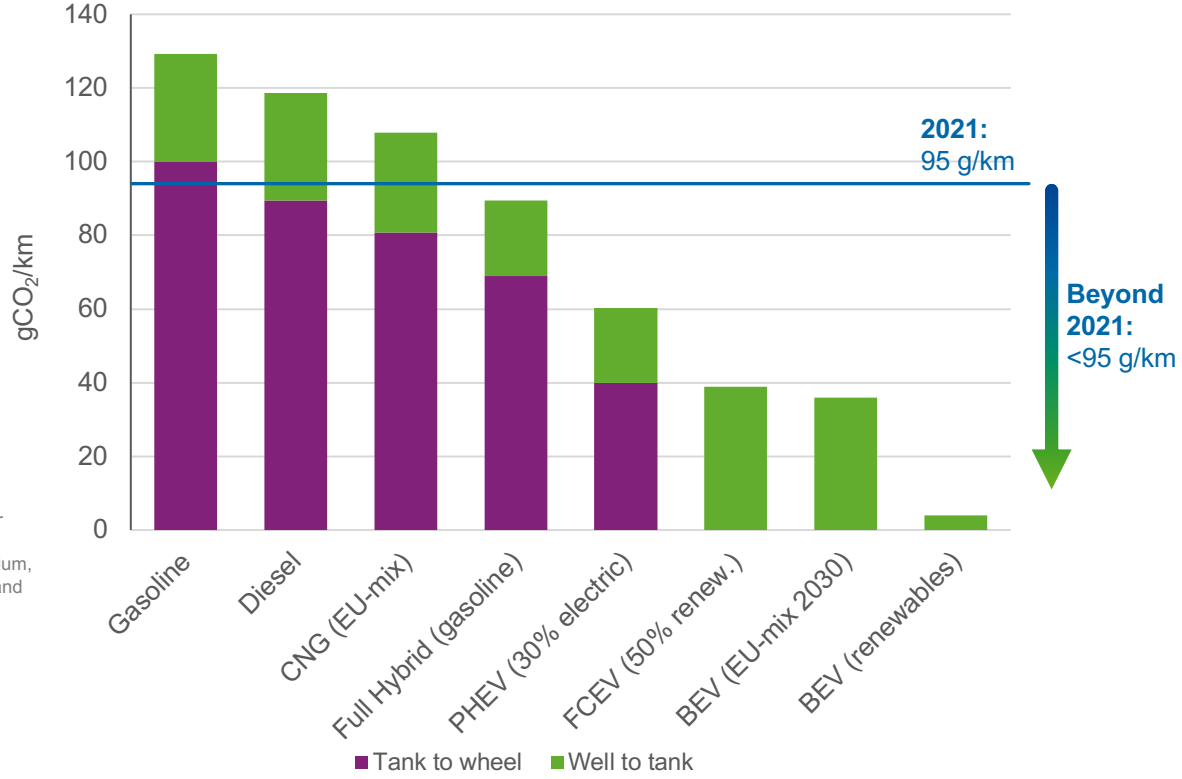
On the road towards clean mobility

Well to wheel sets a clear trend towards BEV….

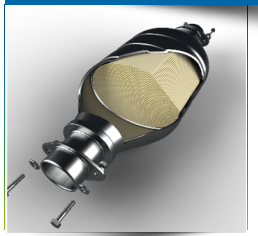


Typical C-segment car

Sources: JEC consortium, Roland Berger study and Umicore estimates

…. but it is an evolution and not a revolution

During which we need:



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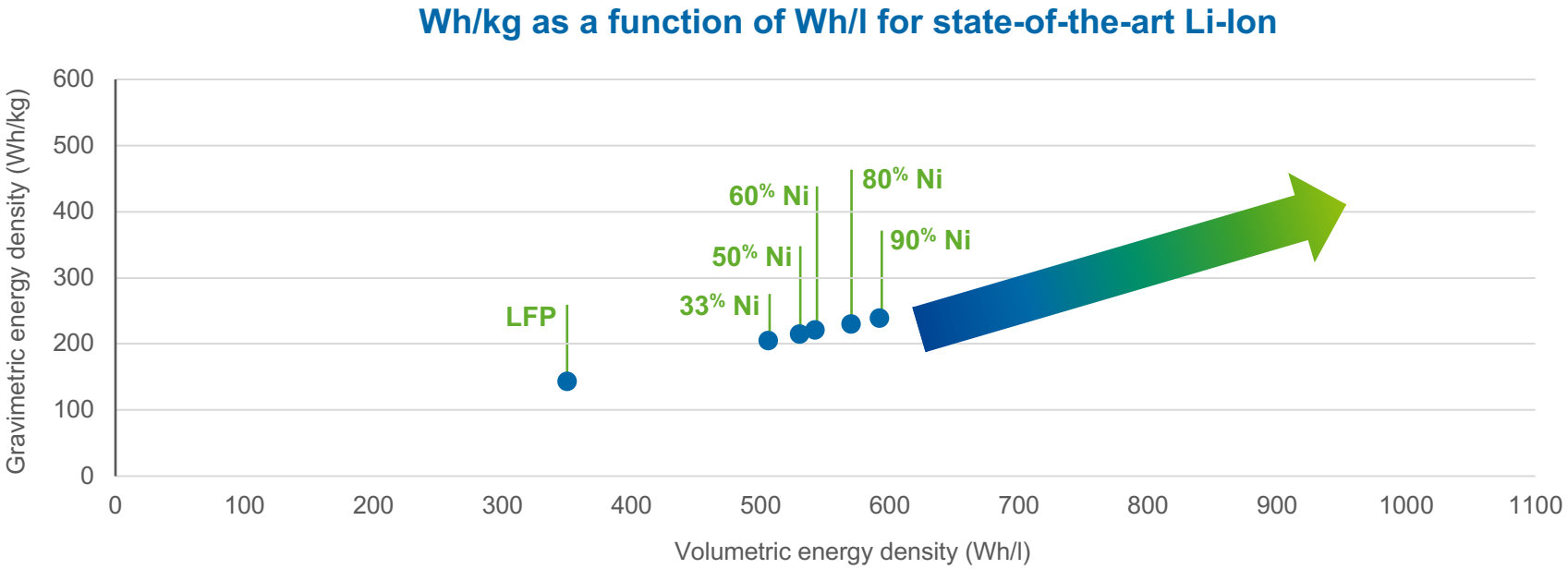
xEV battery materials technologies roadmap

Path towards longer driving range



Car OEMs are looking for the highest (volumetric) energy density

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Umicore's innovation pipeline spans the next 20 years

Driving energy density in today's and tomorrow's Li-Ion batteries

Product R&D: developing the next generation of Li-ion cathode and anode materials

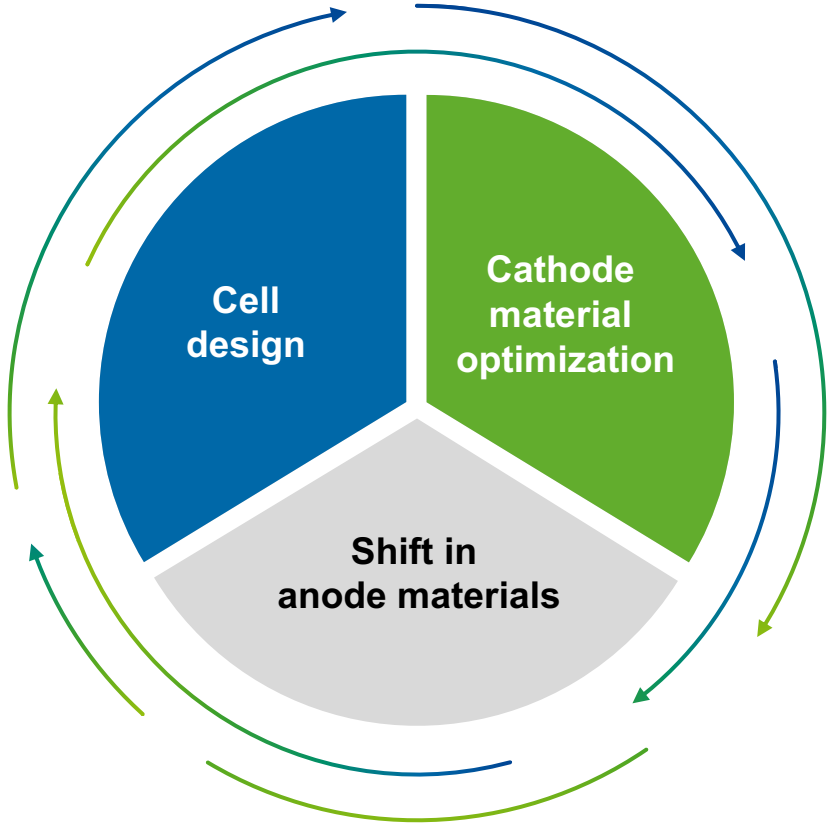
Material optimization and integration into advanced cell designs for ultimate performance

Process R&D: technologies for cost efficient industrial scale production at the highest quality standards

Umicore has an innovative and leading process technology for bringing solutions to mass production

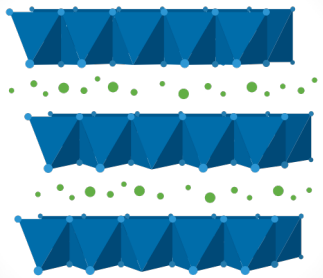
Path towards longer driving range

Strategies to increase the energy density in Li-Ion batteries



Cathode material optimization

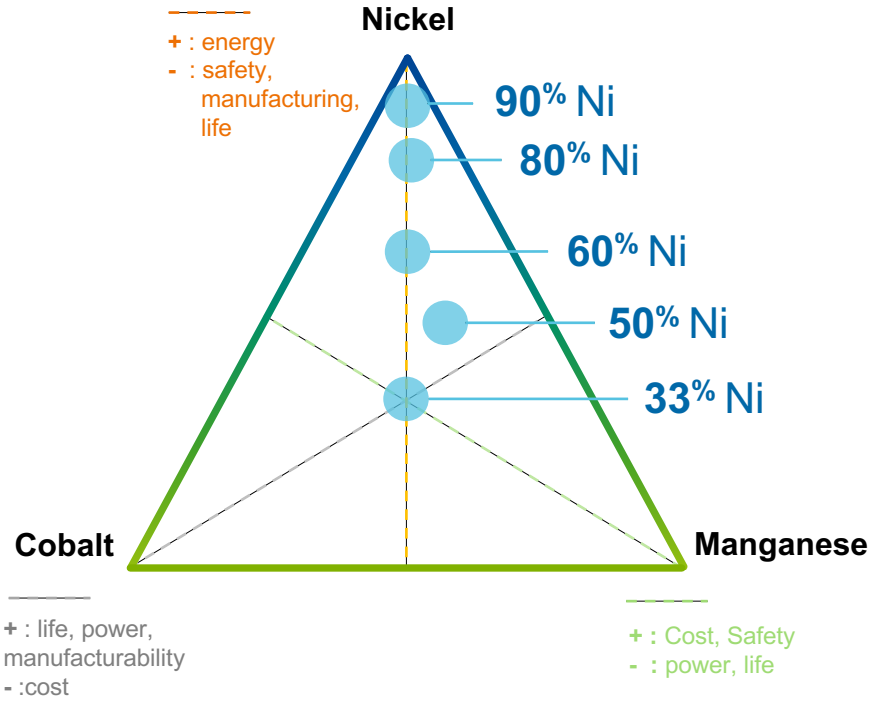
One big family of products



LCO, all grades of NMC, NCA: all layered materials sharing:

- crystal structure
- base manufacturing concepts

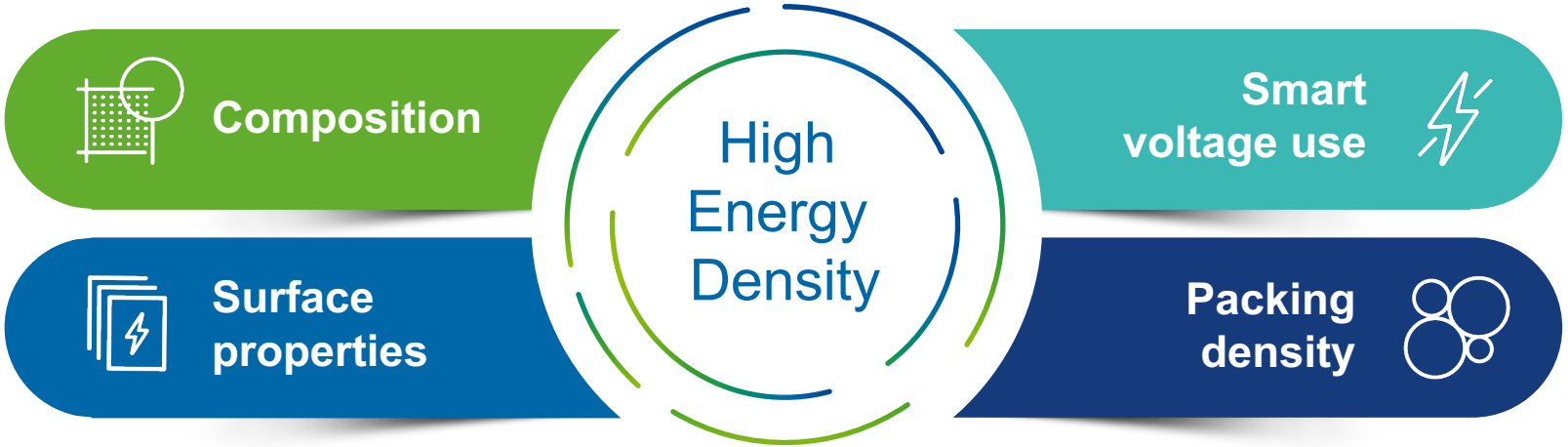
Exact properties depend, among others, on relative ratio metals in metal site



Umicore has the full spectrum of materials in portfolio

Cathode material optimization

Opening the tool box



Several tools at hand to customize cathode materials for customers' key requirements

Differentiation through technology

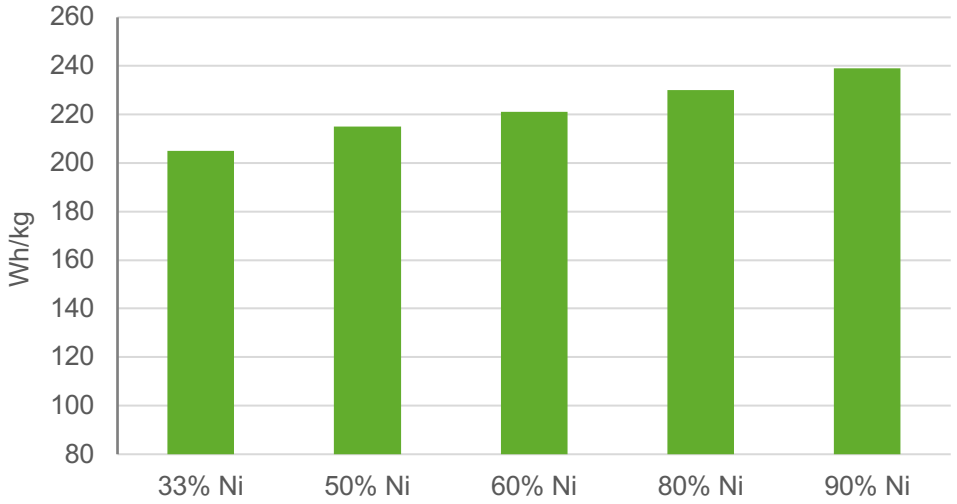
Composition

Cathode material optimization

Higher nickel NMC is an obvious track

- **Energy density increases proportionally** with Ni content in the cathode material
- **Gains up to 17%** could be obtained by moving from 33% to 90% Ni
- Cathode materials need to be **tuned**

Wh/kg as a function of Ni content at constant 4.2V



Umicore's twenty years experience in producing complex cathode materials provides a strong edge to tune cathode materials for higher energy density

smart voltage use

Cathode material optimization

Playing with the voltage window

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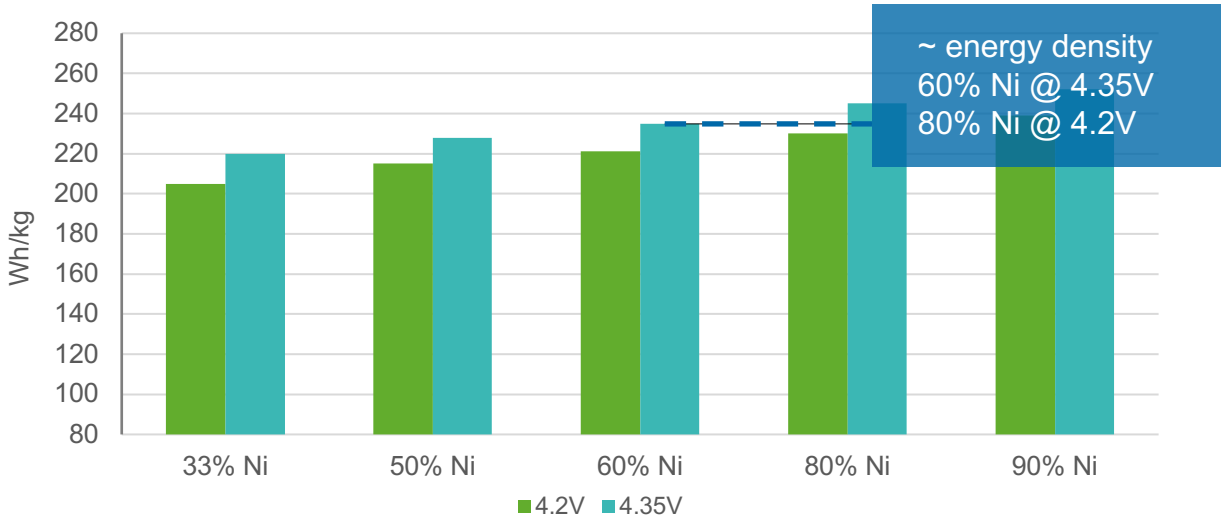
- Standard voltage window for Li-ion cells is 3.0 to 4.2V
- Smart use of voltage window allows **energy density gains of up to 8%** for a given composition
- Cathode materials and their surface need to be **tuned**

Wh/kg as a function of Ni content at 4.2V versus 4.35V



Umicore has patented technologies to engineer and enhance cathode materials and its surface to sustain higher voltages

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packing density

Cathode material optimization

Increase the package density to gain an additional 10%

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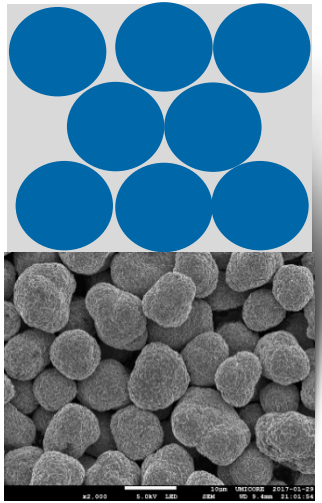
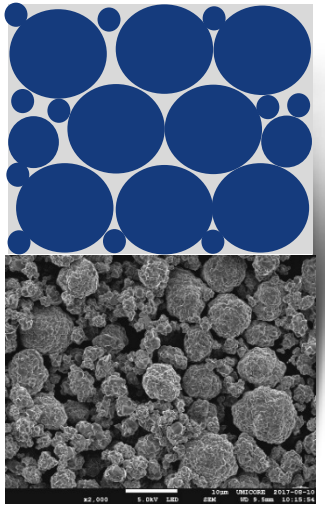
Optimizing the packing density **increases the energy density by another ~10%**



Base packing density



Optimized packing density

Umicore has patented technologies to master the full precursor and cathode material flowsheet for ultimate performance

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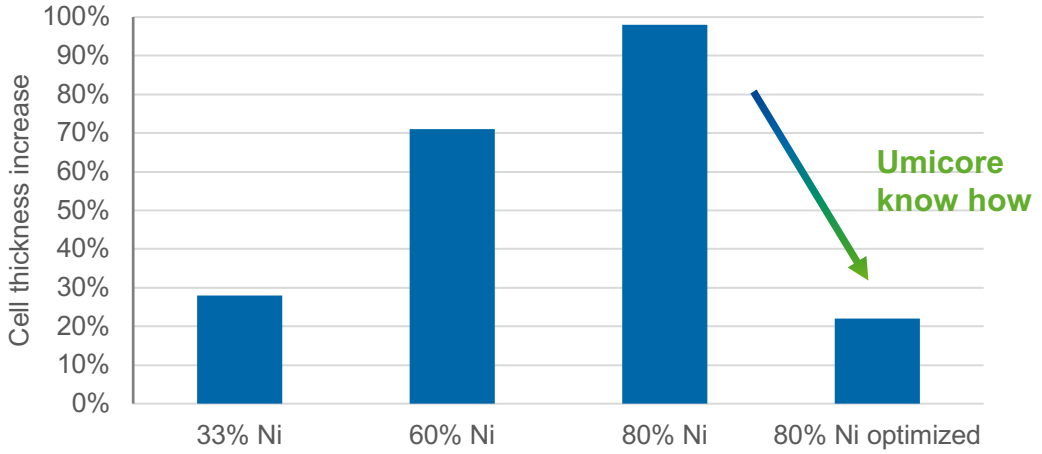
surface properties

Cathode material optimization

Enabling use of high nickel in large pouch designs

- Gas generation is correlated to nickel content in the cathode material
- So far, this has limited the use of Hi Ni to small rigid cell formats

Thickness increase as a function of Ni content at constant 4.2V and 90°C



By focused surface engineering (patented technologies), Umicore enables usage of Hi Ni materials in large pouch format cells

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Cathode material optimization

Is higher nickel the holy grail?

High nickel is part of the solution towards higher energy density

However, basic fundamental drawbacks must be considered:

- Technology limitations:
  - *Cycle life: not yet on a par with lower Ni compounds*
  - *High voltage stability and safety yet to be demonstrated*
  - *Limited experience of integration into large cells at battery makers*
- Performance comes at a cost
- Industrial application at 90%+ Ni yet to be demonstrated

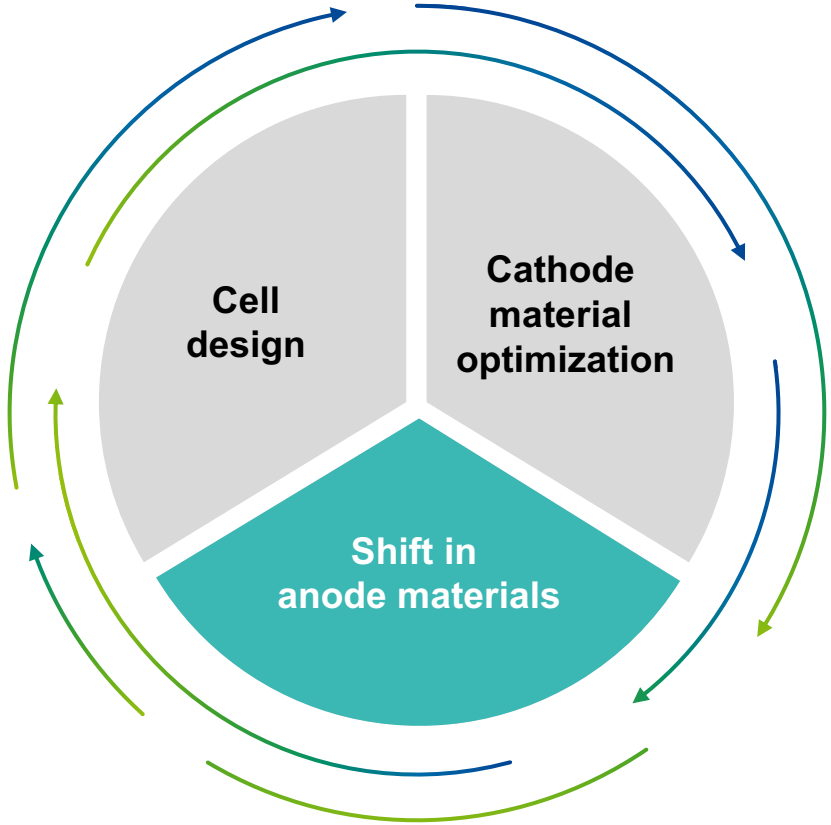
Through technology Umicore can address some of these drawbacks

The full spectrum of chemistries is and will be needed to serve customers' requirements

Umicore offers the full range of lithium layered cathode materials - all certified for the most stringent automotive requirements

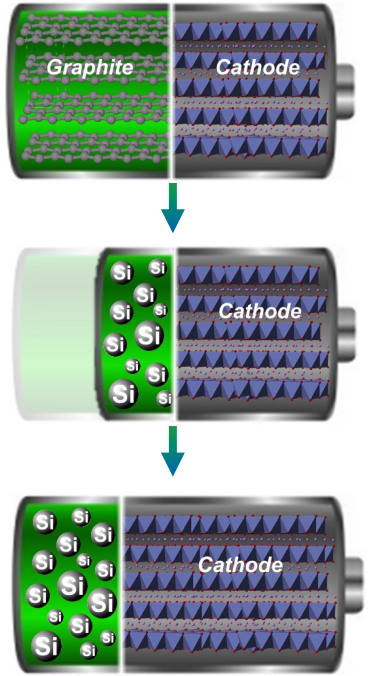
Path towards longer driving range

Strategies to increase the energy density in Li-Ion batteries



Shift in anode materials

From graphite to silicon

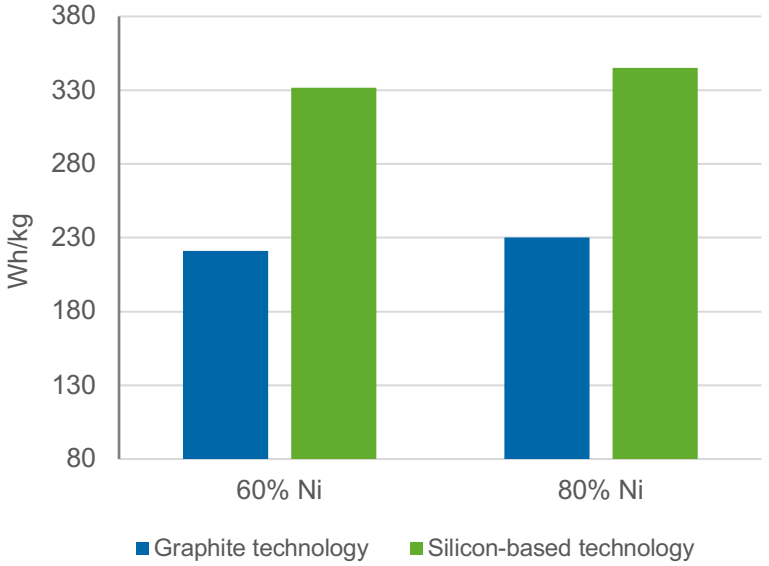


Current graphite anodes are replaced by **high capacity silicon based anodes**

Capacity 2-10 times higher than today's graphite technology

Potential to **increase energy density** of batteries **up to 50%** versus current state-of-the-art technology

Wh/kg as a function of Ni content with graphite and silicon based anode technology



xEV roadmaps push for Si-based anodes

Swelling remains a major drawback

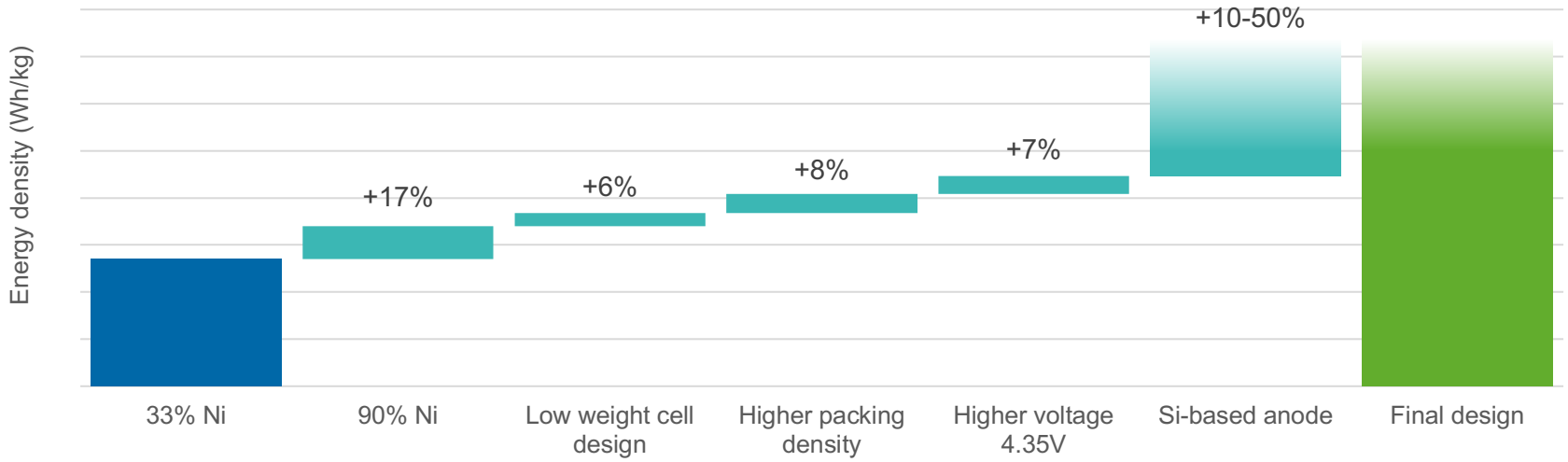
During charge:
volume of silicon intrinsically expands by 300%

Umicore has developed a unique material to avoid excessive electrolyte reactions during swelling and contractions

Umicore is currently in product qualifications for its first generation of silicon-based anode materials with several customers

Path towards longer driving range

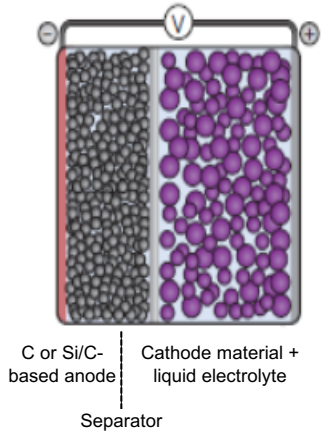
In a liquid state Li-Ion Battery



A smart integration of optimized active (cathode and anode) materials into advanced cell design will allow xEV battery materials producers to offer their customers the targeted driving range (500-700km range)

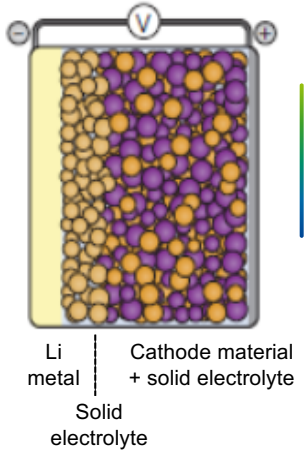
Path towards longer driving range

When the liquid electrolyte becomes the limiting factor



Liquid state

ED target:
280Wh/kg
660Wh/L



Solid state

ED target:
500Wh/kg
1000Wh/L

Solid state battery:

- Solid inorganic or polymer **electrolyte**
- Li-metal **anode**
- Tailor-made **cathode materials**

Umicore's twenty years experience in producing complex cathode materials provides a strong edge to tune cathode materials for solid state batteries

Umicore is currently developing in collaboration with customers cathode materials for solid state batteries

Solid state batteries

Still on lab and pilot scale

There are many advantages….

- Higher safety (no liquid organic electrolyte)
- Increased temperature stability
- High energy density
- Easier integration into a pack (simplified thermal management)

Solid state batteries are on major OEMs' roadmaps

… yet some drawbacks to be overcome

- Electrolyte conductivity
- Materials stability and purity
- Processing issues

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Path towards longer driving range

What could be next on the roadmap?

Li-Sulphur

+ good gravimetric energy density and potentially low cost

- low volumetric energy density
- limited power
- limited cycle life

Li-air

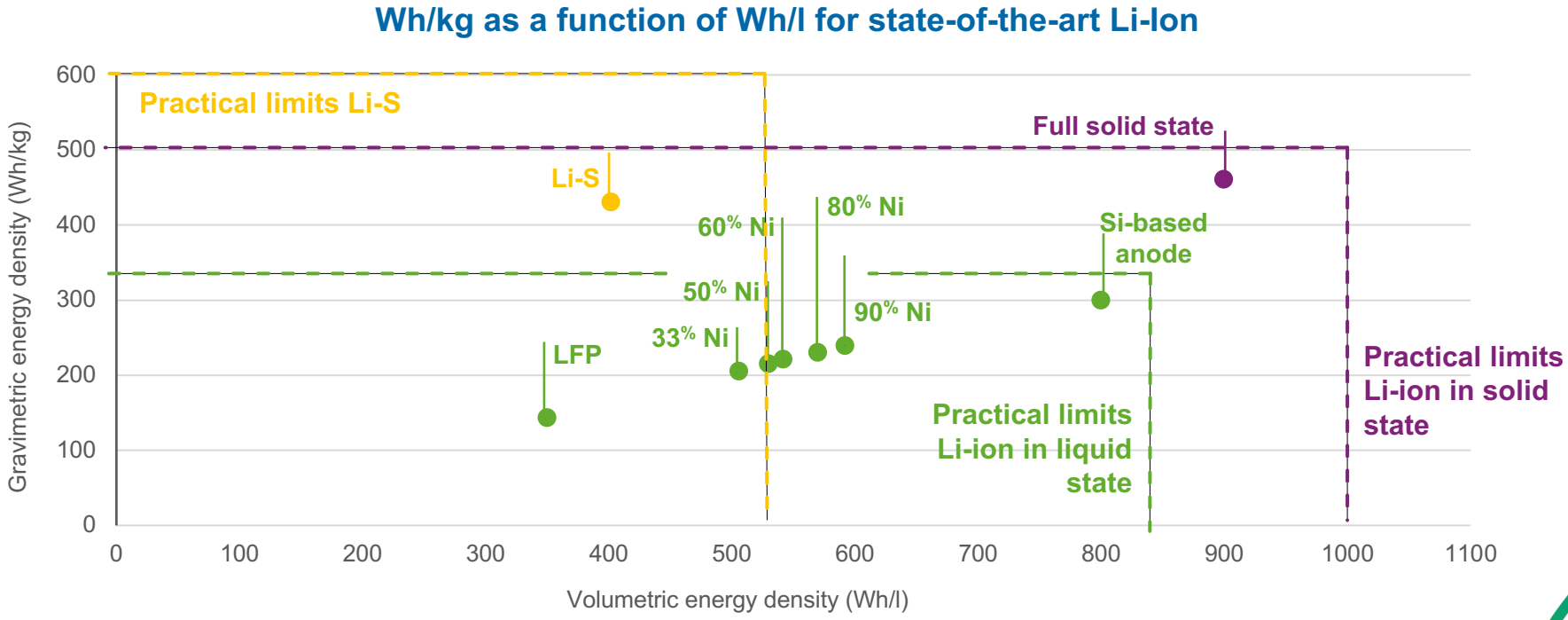
+ very high theoretical gravimetric and volumetric energy density

- low cycle life
- proof-of-concept only on lab scale; no tangible progress despite huge academic R&D efforts

Potential disruptive technologies unlikely to play a role in automotive applications in the foreseeable future due to critical limitations and/or low technology readiness level

Path towards longer driving range

Conclusions



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Agenda

Well to wheel efficiency considerations

Key developments in xEV battery materials

Key developments in fuel cells

Wrap-up

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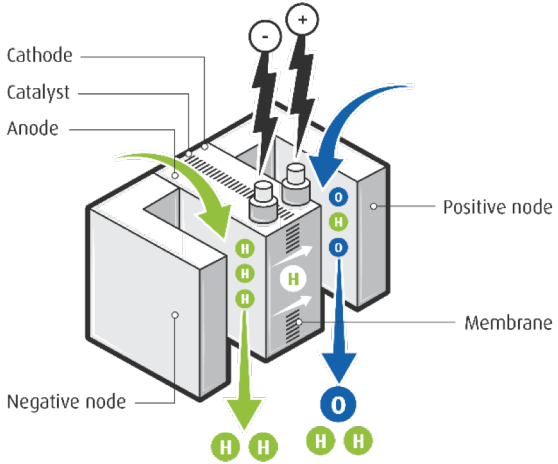
Fuel cell drivetrains are gaining traction

Technical drivetrain maturity achieved and demonstrated by several OEMs



- Fuel cells generate electricity using hydrogen as the energy carrier
- Hydrogen reacts with oxygen, creating electricity
- The electro catalyst sets this chemical reaction in motion

The catalyst is a key driver for cost and performance

Umicore has been developing fuel cell catalysts for close to 30 years:

Competitive product and R&D portfolio

Strong positioning in existing OEM platforms and 2020+ development programs

Fuel cells drivetrains

Provide superior range and better refueling time than BEV

It provides the best of both worlds:

- Zero emissions ~ BEV
- Driving range and refuelling time ~ internal combustion engines

Fuel cell technology fits for long range applications, in particular trucks

But there are still some drawbacks to overcome:

- **Cost:**
  - Lower Pt utilization and enhanced system design (through advanced fuel cell catalysts)
  - Economy of scale
- **The need for worldwide infrastructure programs:** targeting for basic coverage in 2025

Agenda

- Well to wheel efficiency considerations
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- Key developments in fuel cells
- **Wrap-up**

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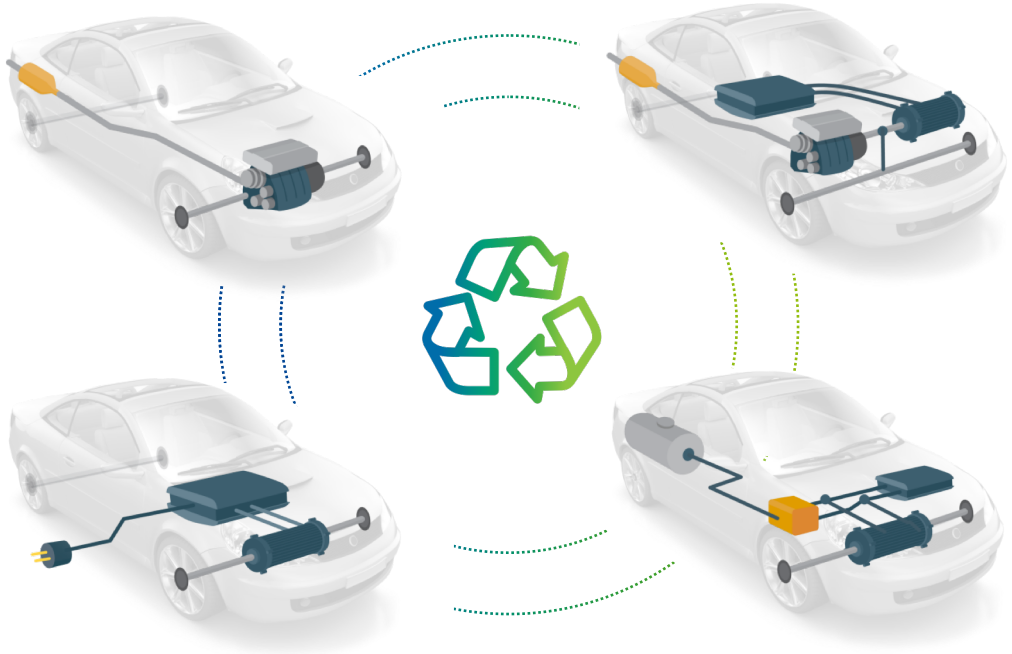
Unique position in technology roadmap for clean mobility materials

ICE
Emission control catalysts

BEV
Battery materials



(p)HEV
Battery materials and emission control catalysts

Fuel cells
Electro-catalyst and battery materials

The roadmap towards clean mobility = technology driven

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