Co-Extrusion: Advanced Manufacturing for Energy Devices

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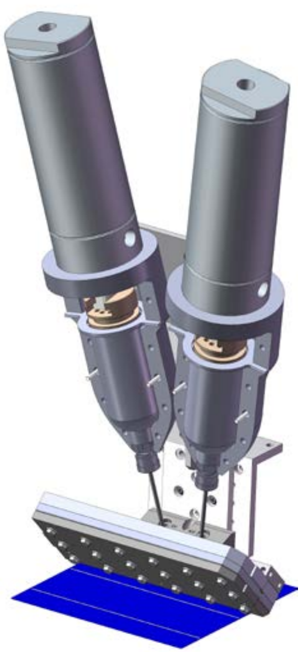
Co-Extrusion (CoEx) for Energy Devices

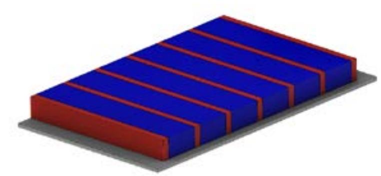
- CoEx is deposition technology developed at PARC for “printing” high aspect ratio features with highly loaded, viscous inks
- Applications: To date, CoEx has been applied to solar cell metallization and battery electrodes



CoEx Technology

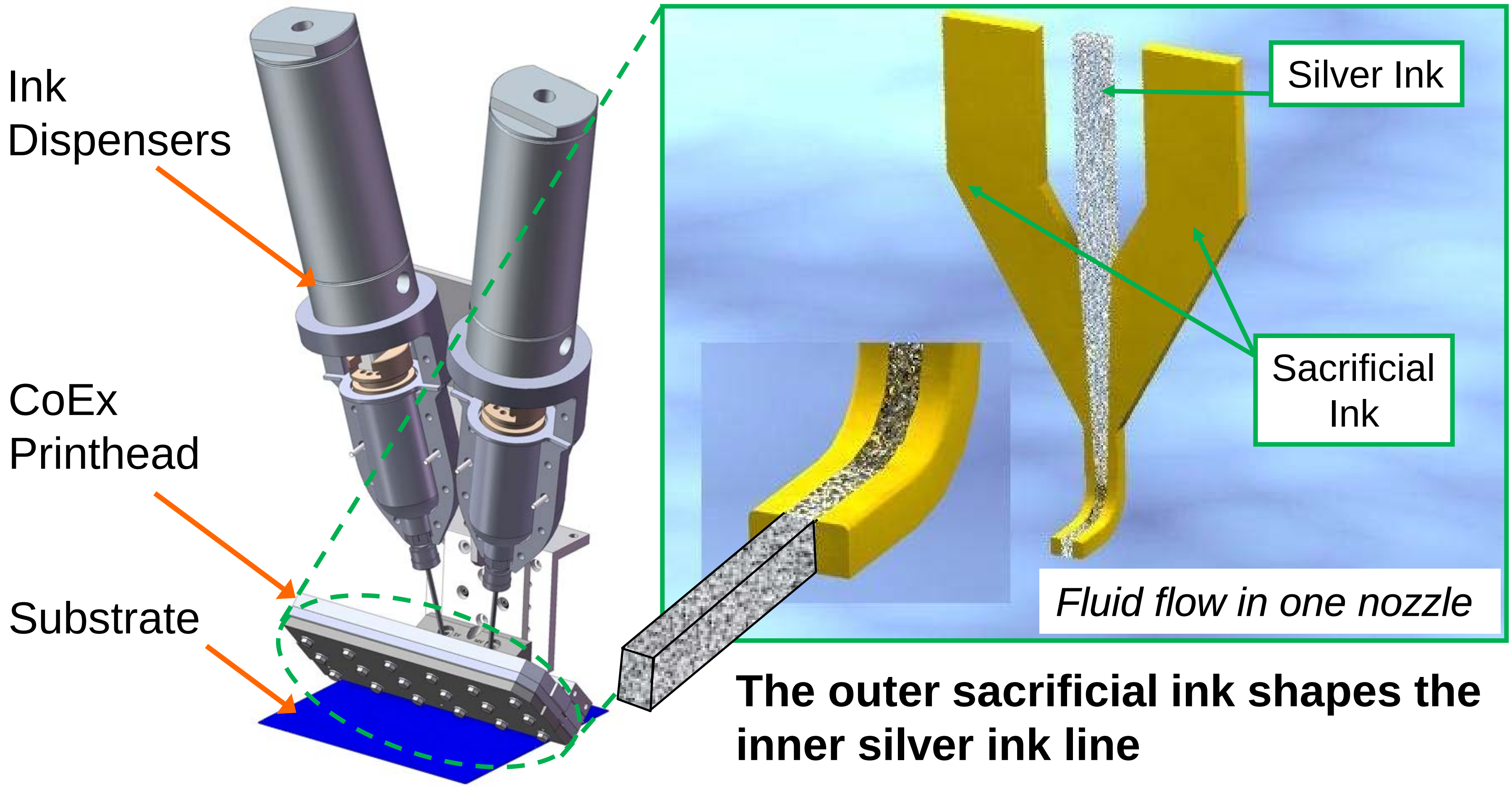
Higher Efficiency
Solar Cells

Higher
Energy/Power
Battery Electrodes



Co-Extrusion (CoEx): How it Works

First applied to printing silver metallization lines on solar cells

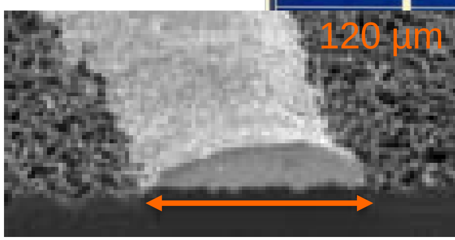


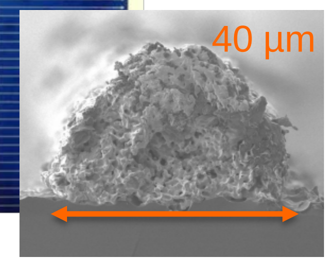
The outer sacrificial ink shapes the inner silver ink line

Co-extrusion (CoEx) for Solar: Printing Metal Gridlines on Solar Cells

Screen printed front side metallization

Co-extruded front-side metallization



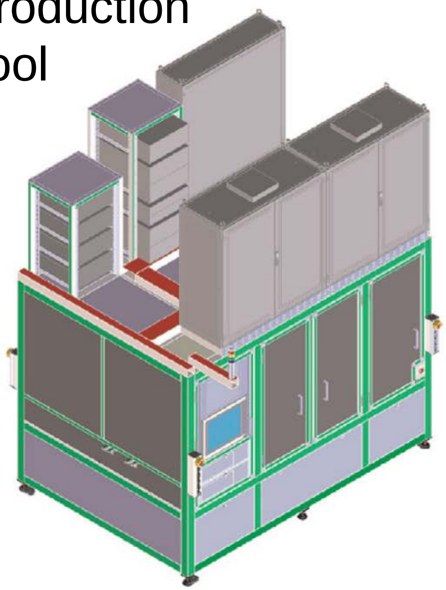


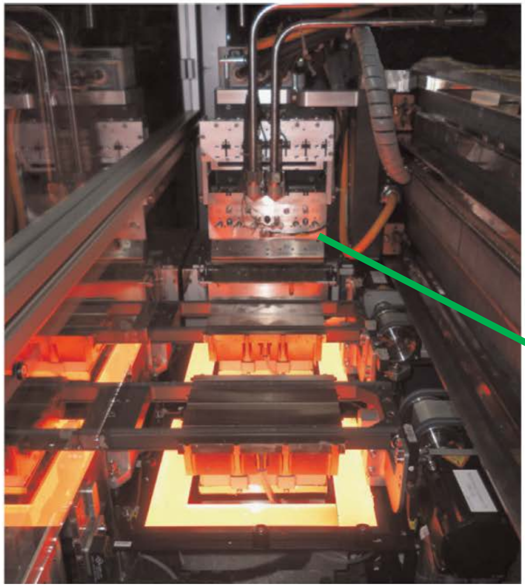
- By getting <u>more height on the gridlines</u>, they can be made narrower compared to screen printing, thus covering less of the surface area of the solar cell
- This technique can yield a 3 to 6% relative efficiency benefit
- A 100 MW fab turns into a 103 to 106 MW fab!

L.P. Richter, G. Fischer, L. Sylla, M. Hentsche, S. Steckemetz, M. Müller, C.L. Cobb, S.E. Solberg, R. Rao, S. Elrod, P. Palinginis, E. Schneiderlöchner, H. Neuhaus, "Progress in Fine Line Metallization by Co-extrusion Printing on Cast Mono Silicon PERC Solar Cells," *Solar Energy Materials and Solar Cells,* Vol. 142, pp. 18-23, 2015. doi:10.1016/j.solmat.2015.05.023

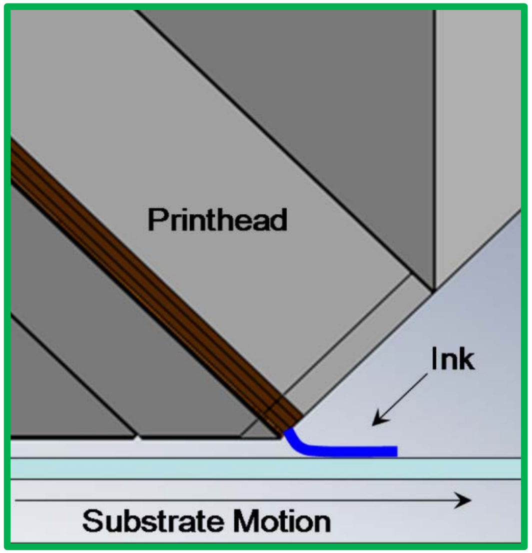
CoEx for Solar at Pilot Production Scale

Production Tool



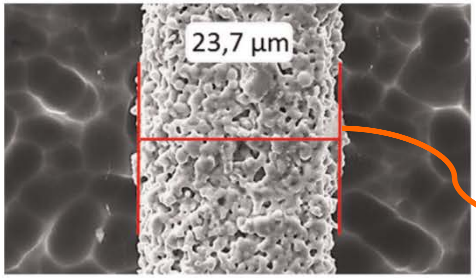


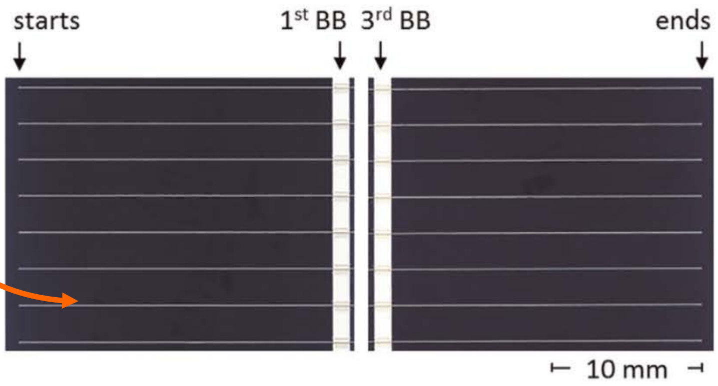
- In 2015, demonstrated record efficiency of 21.42%
- CoEx has integrated into high speed, high volume production



Side View of CoEx process

Top View





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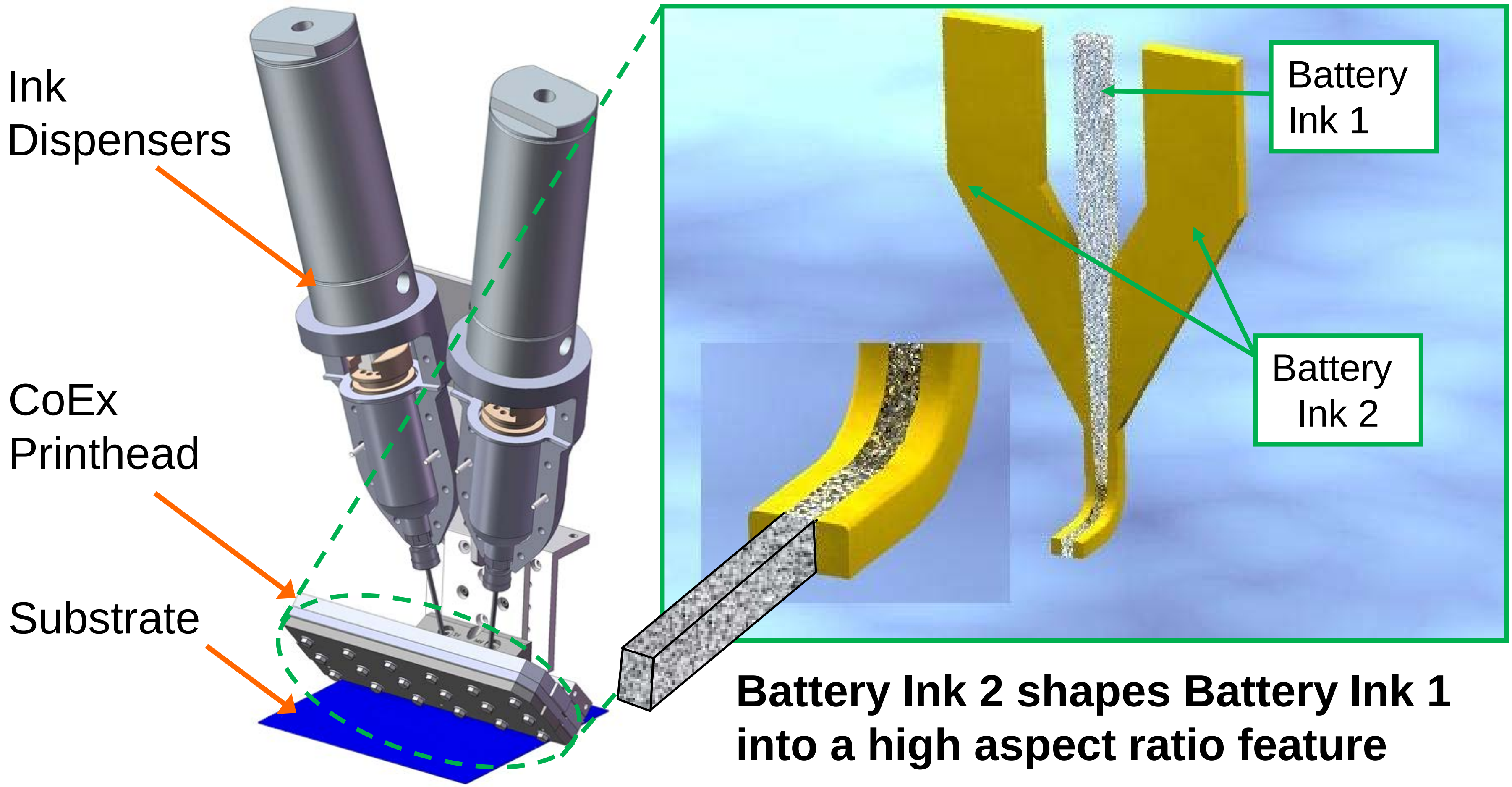
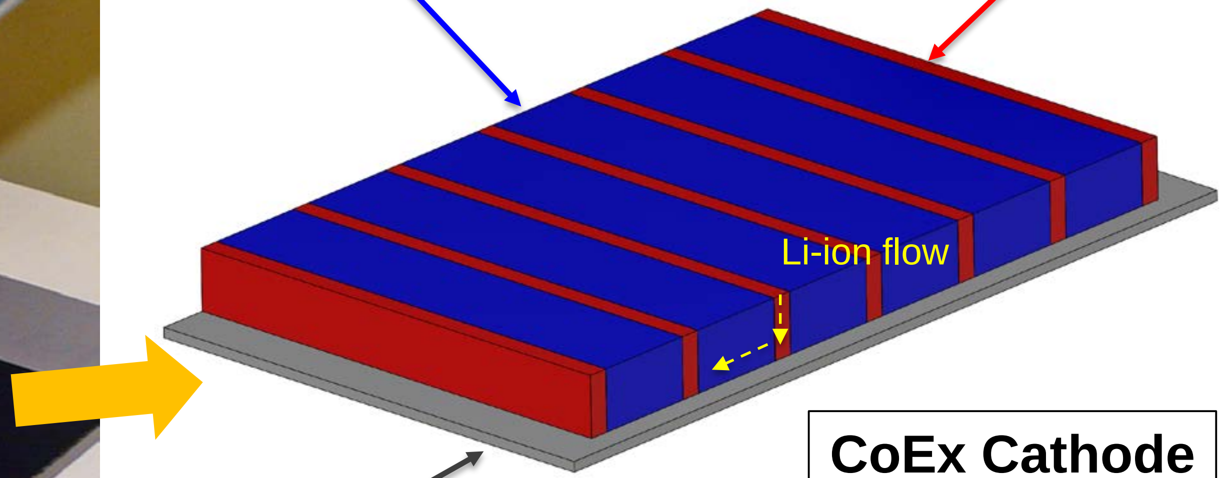
Co-Extrusion (CoEx): Applying Solar Technology to Battery Electrodes for Electric Vehicles (EVs)



Battery Ink 2 shapes Battery Ink 1 into a high aspect ratio feature

Co-Extrusion (CoEx) for Enhanced Ion Transport in Thick Battery Electrodes

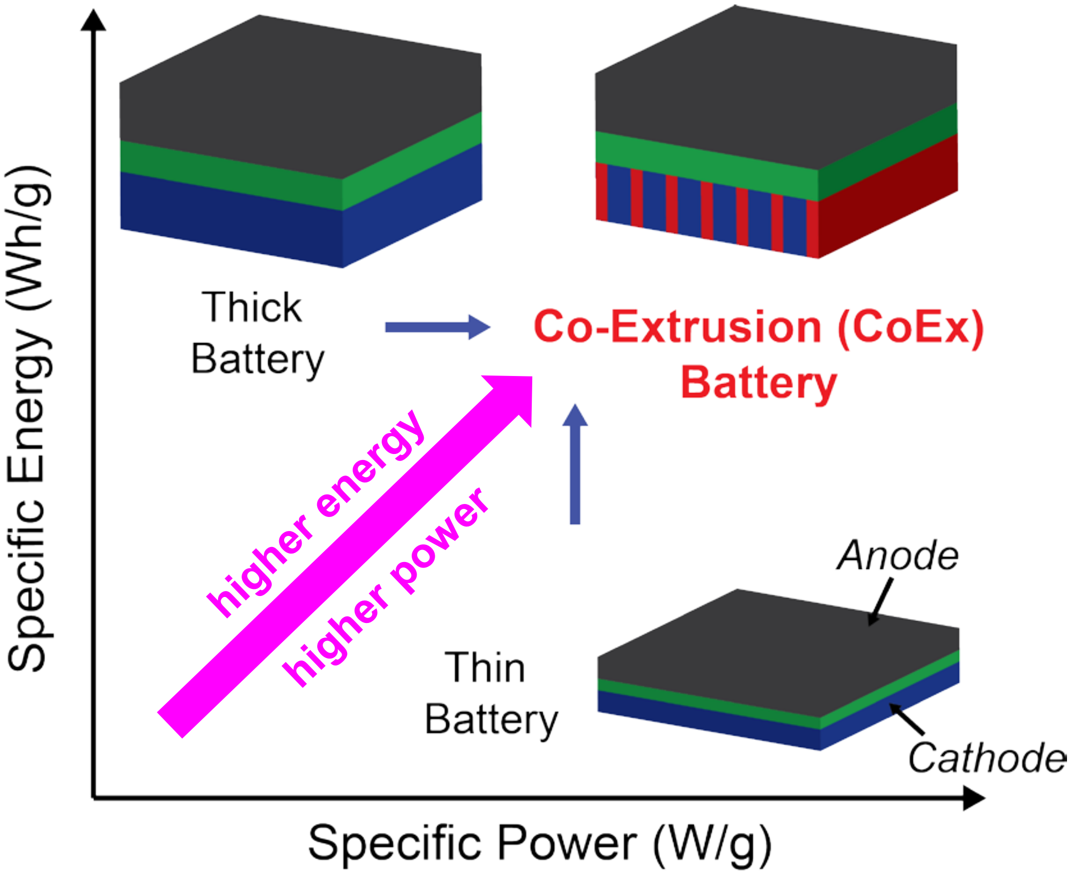
Co-Extrusion Printhead*



Hypothesis: Using conventional battery materials, thick CoEx electrodes can change conduction pathways in lithium-ion batteries, decoupling power and energy trade-offs with novel geometry layout

*ARPA-E Award Number DE-AR0000324

Lithium Ion Batteries for Electric Vehicles (EVs)



- Thin electrodes → high power
- Thick electrodes → high energy
- 2D & 3D battery designs show great promise for high energy and high power batteries
- Large-area, low cost processes are required to realize the benefits of 2D & 3D battery designs → **CoEx**

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Batteries for Electric Vehicles

110 miles per charge

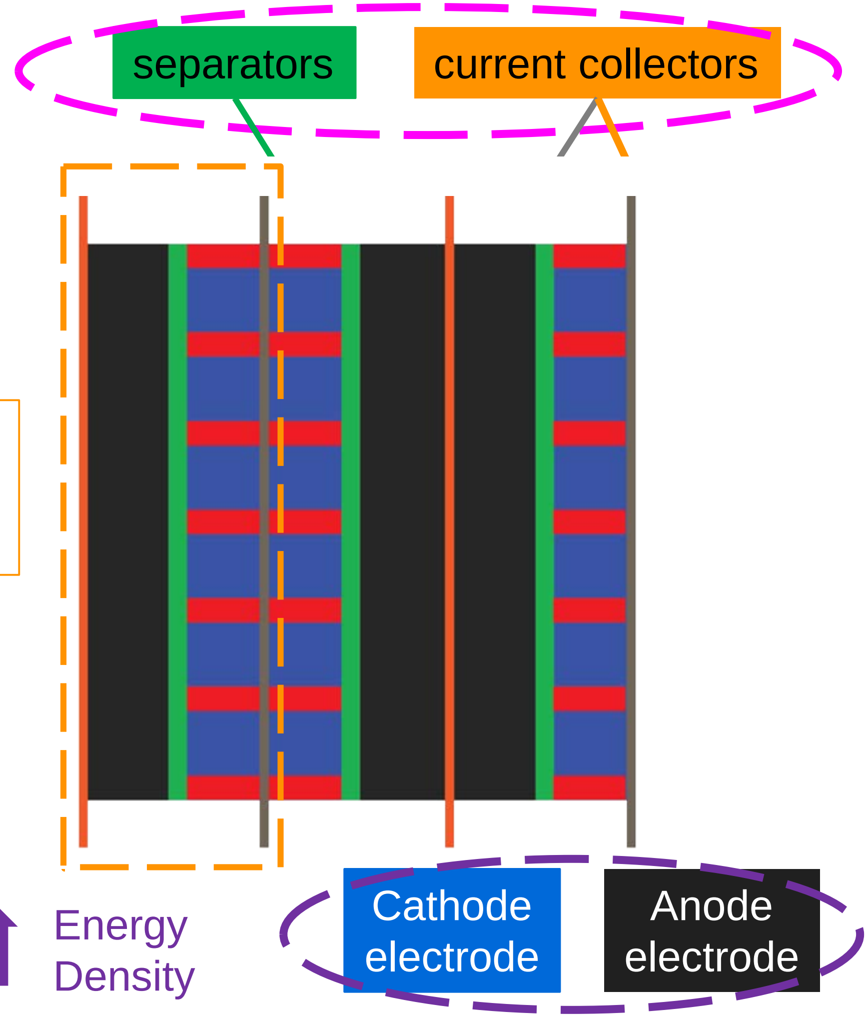
Image Source: Ford Motor Company

EV Battery Module

Pouch Cell

Expensive purchased components

Single Electrode Stack



Energy Density

Conventional Pouch Cell Stack

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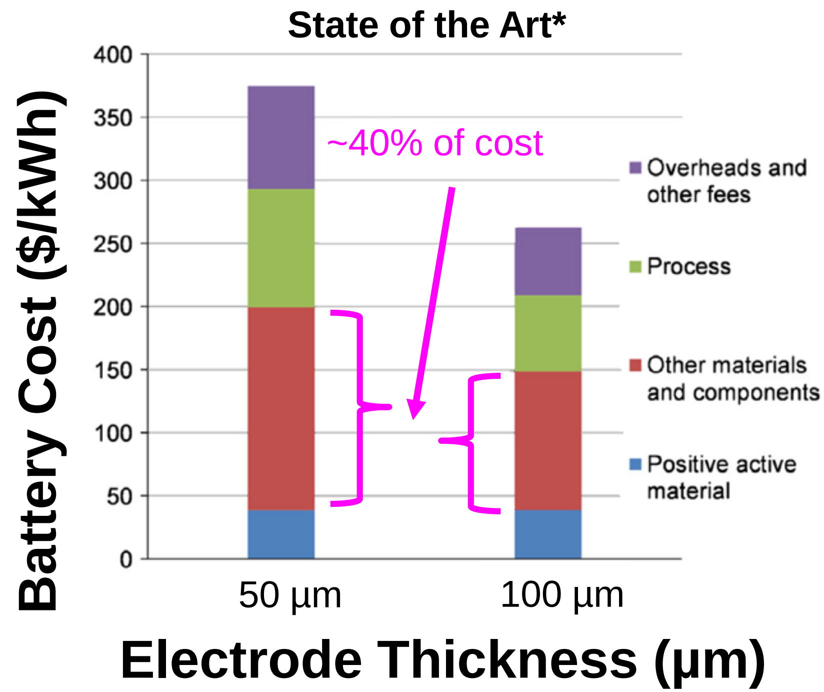
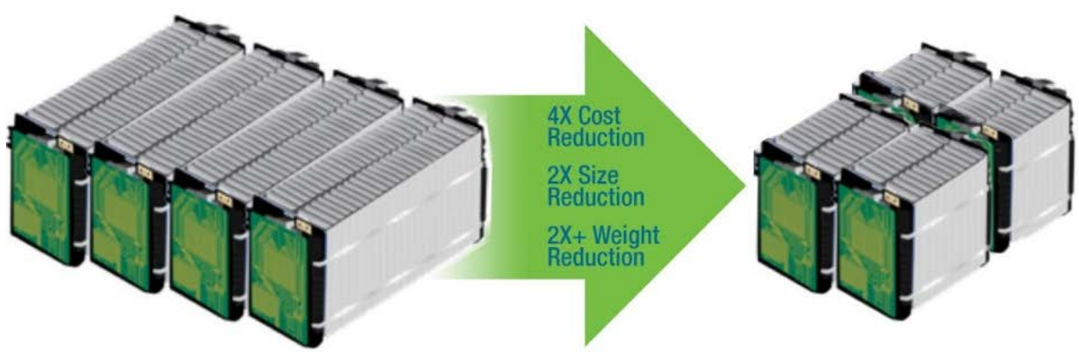
Challenges for Batteries in Transportation

- **Department of Energy (DOE)** calls for **reducing the cost, volume, and weight** of batteries for electric vehicles (EVs) while simultaneously **improving performance**
- **Lithium-ion batteries (250 Wh/kg)** are the most popular chemistry option, but their high cost is a barrier to widespread adoption





2012

$500/kWh, 100 Wh/kg, 200 Wh/L

2022

$125/kWh, **250 Wh/kg**, 400 Wh/L

Radical changes to **manufacturing** are required for a drastic **$/kWh cost reduction** and performance increase

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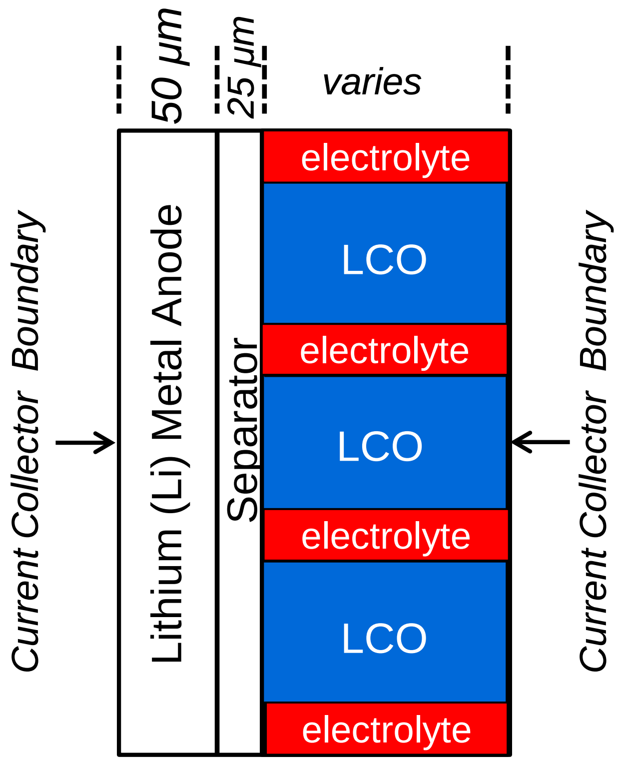
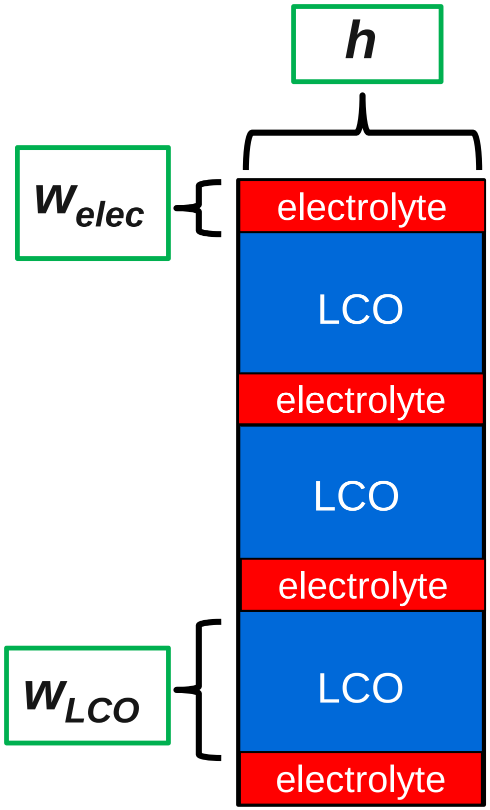
*Source: G. Patry et al., *Energy Science and Engineering* (2015)

CoEx Geometry Exploration with Macrohomogeneous Porous Electrode Model in COMSOL

What are the required thicknesses and feature sizes for a CoEx cathode electrode?



Half Cell Geometry



Cathode Structure

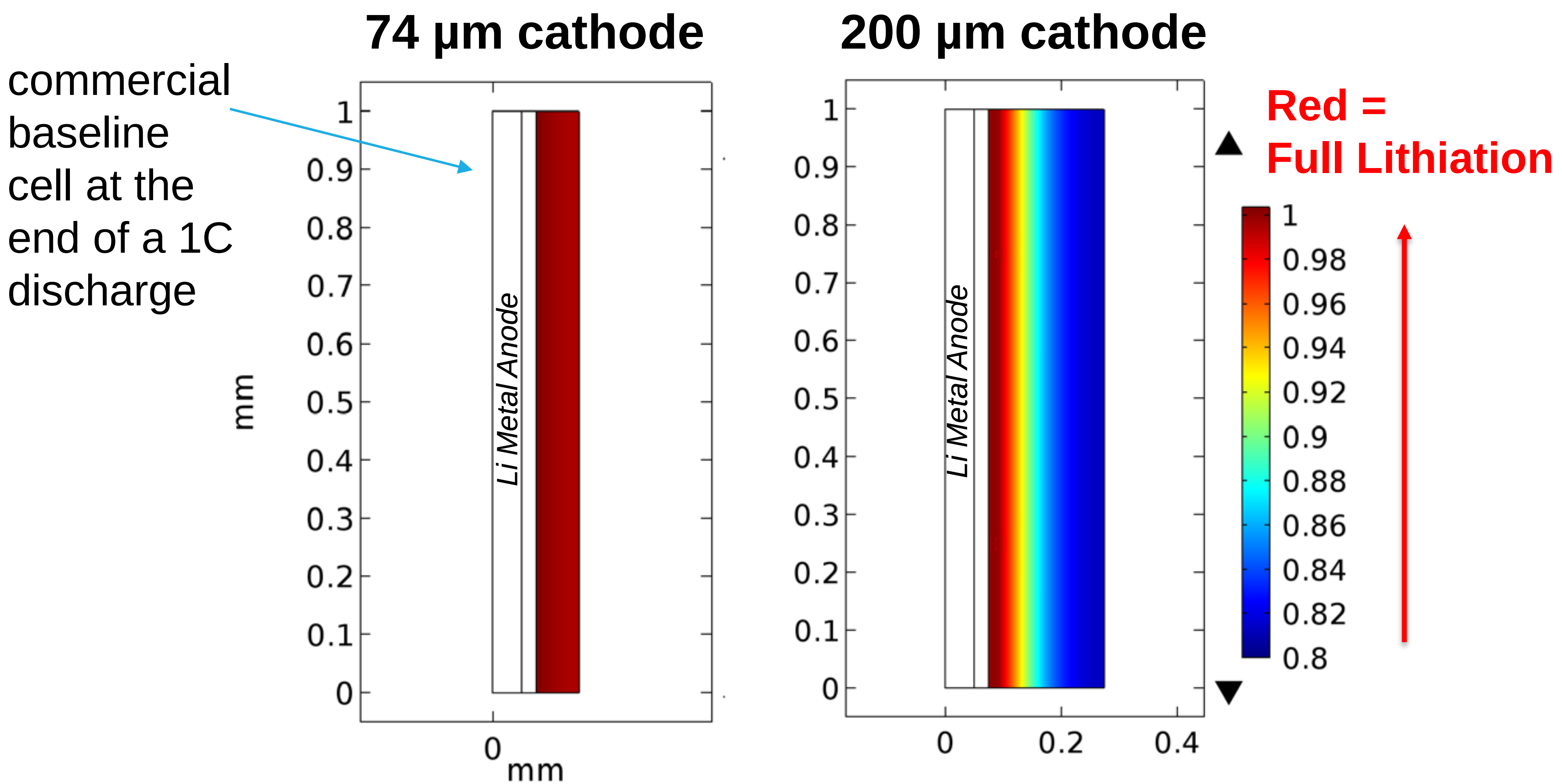
LCO Composition:
52% $LiCoO_2$
14.2% Filler/binder
33.8% Porosity

Electrolyte:
1:1 EC:DMC
1M $LiPF_6$

LCO = Lithium Cobalt Oxide ($LiCoO_2$)

M. Doyle, T.F. Fuller, J. Newman, *J. Electrochem. Soc*. 140 (1993) 1526-1533.
T.F. Fuller, M. Doyle, J. Newman, *J. Electrochem. Soc*., 141 (1994) 1-10.
C.L. Cobb and M. Blanco, *Journal of Power Sources*, Vol. 249, pp. 357-366, 2014.

Lithium Utilization Plots – Conventional Cells
(End of a 1C Discharge Cycle)

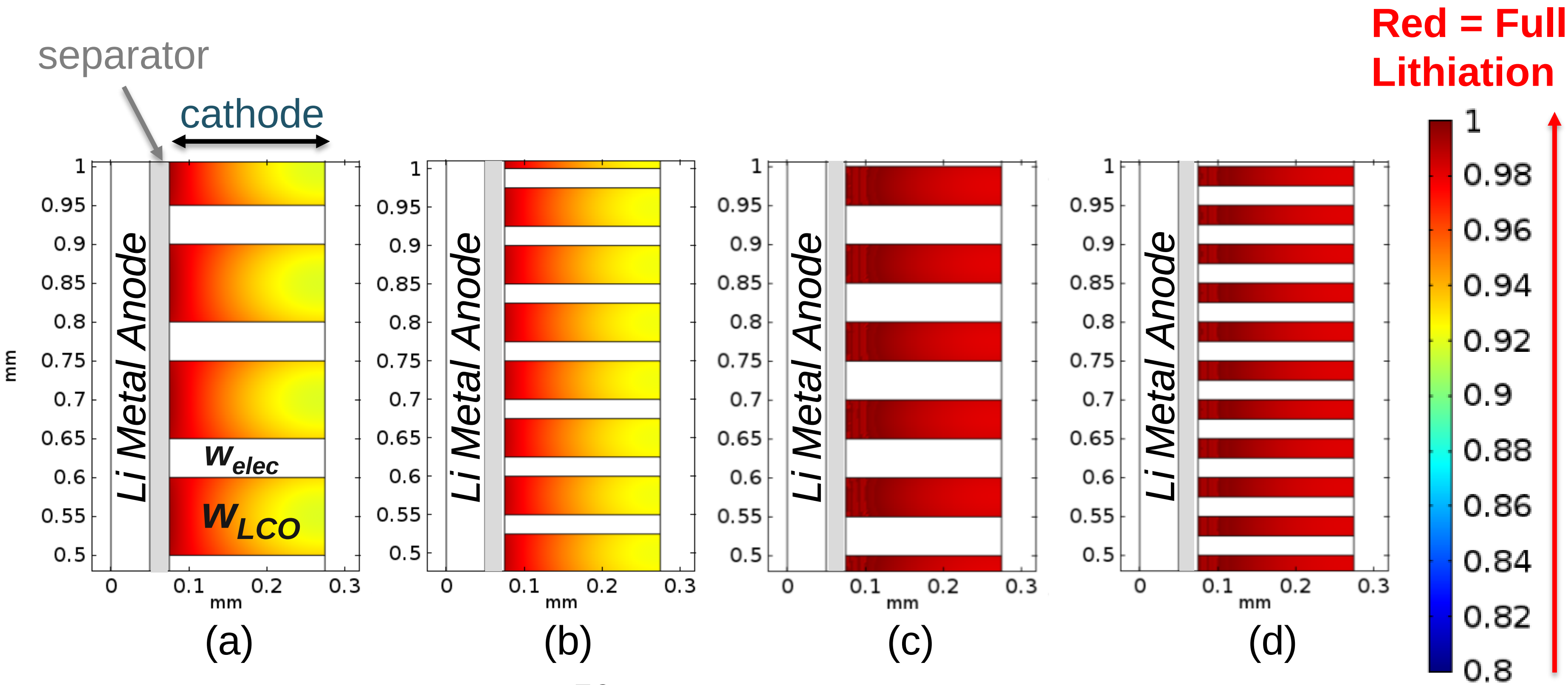


Note: COMSOL model was compared against DUALFOIL and a conventional 1D COMSOL model and before moving to 2D models

Parameters from: G. Ning, R.E. White, B.N. Popov, Electrochimica Acta 51(10) (2006) 2012-2022

Source: **C.L. Cobb** and M. Blanco, *Journal of Power Sources*, Vol. 249, pp. 357-366, 2014.

Lithium Utilization Plots – 200 µm Thick CoEx Cathodes
(End of a 1C Discharge Cycle)



w_{LCO}=100 µm
w_{elec}=50 µm

w_{LCO}=50 µm
w_{elec}=25 µm

w_{LCO}=50 µm
w_{elec}=50 µm

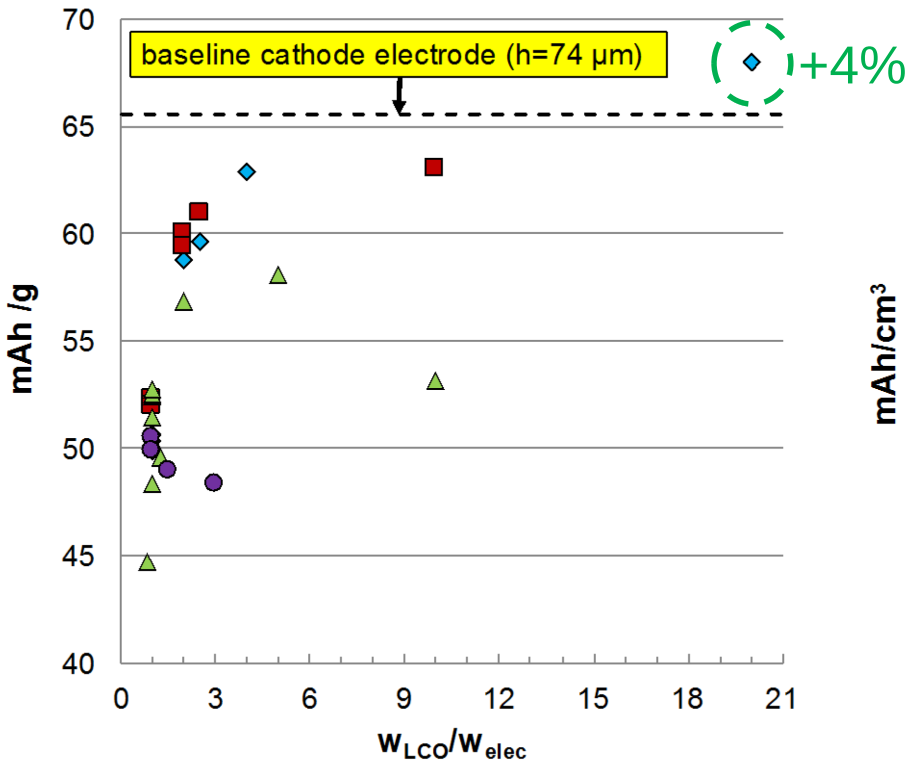
w_{LCO}=25 µm
w_{elec}=25 µm

1C discharge rate results shows that designs (c) and (d) have the best performance based on specific capacity

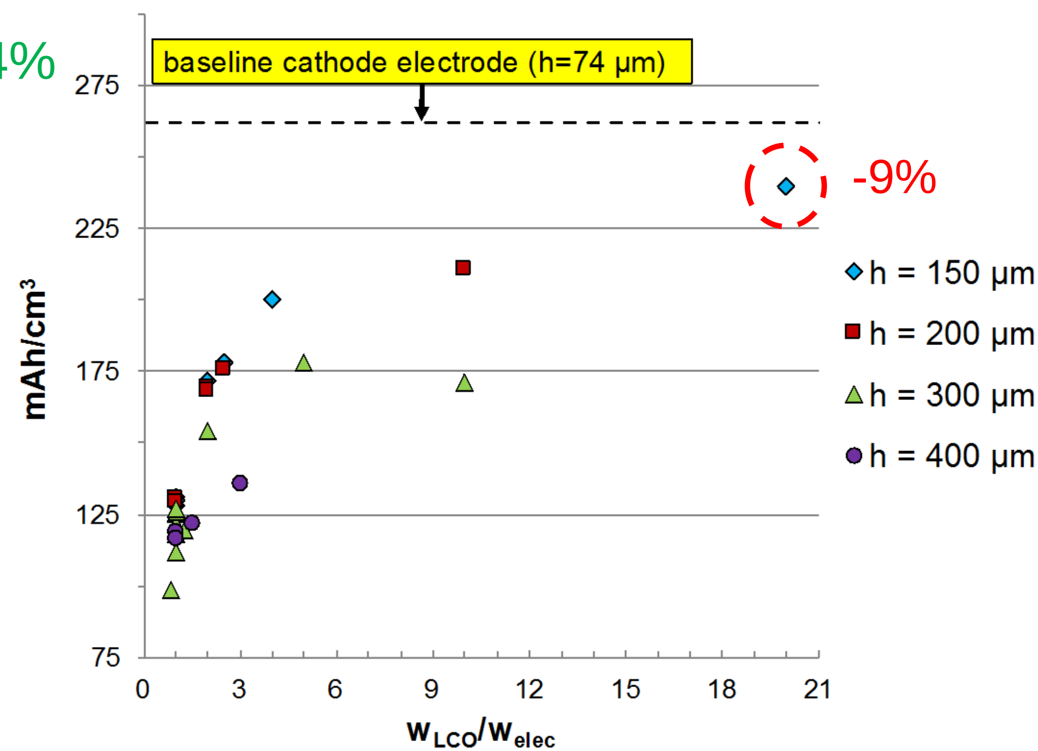
Source: **C.L. Cobb** and M. Blanco, *Journal of Power Sources*, Vol. 249, pp. 357-366, 2014.

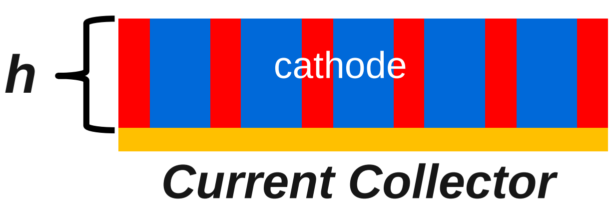
Capacity of a Single CoEx Cathode Layer

Gravimetric capacity vs. ratio of co-extruded pillar widths



Volumetric capacity vs. ratio of co-extruded pillar widths



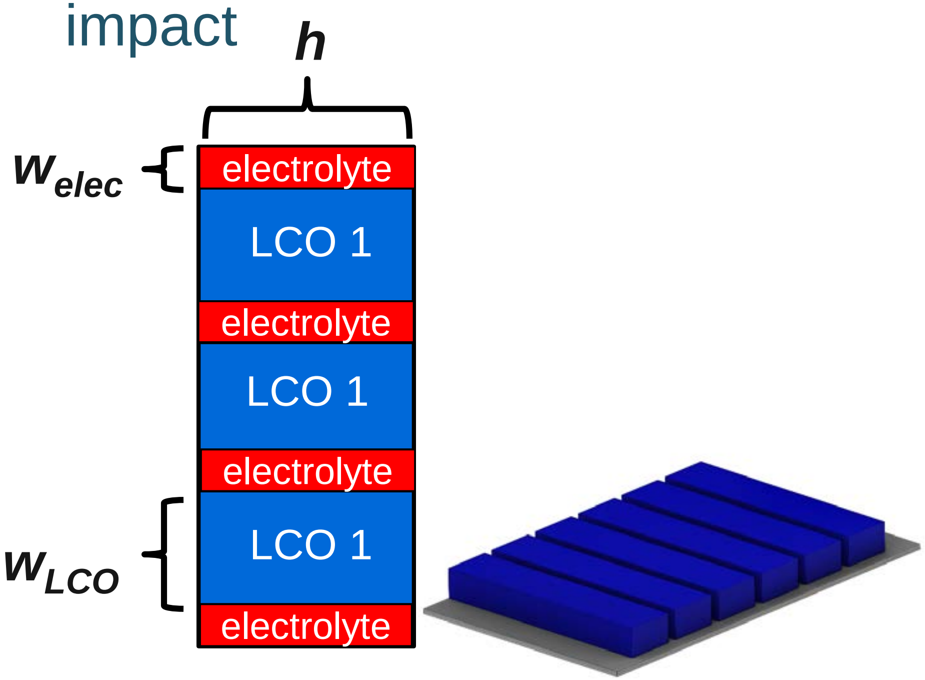


Result: 150 µm thick CoEx cathode with $w_{LCO}/w_{elec} = 20$ was the best performing design & translates to a <u>~15% improvement in gravimetric capacity</u> at the pouch cell level

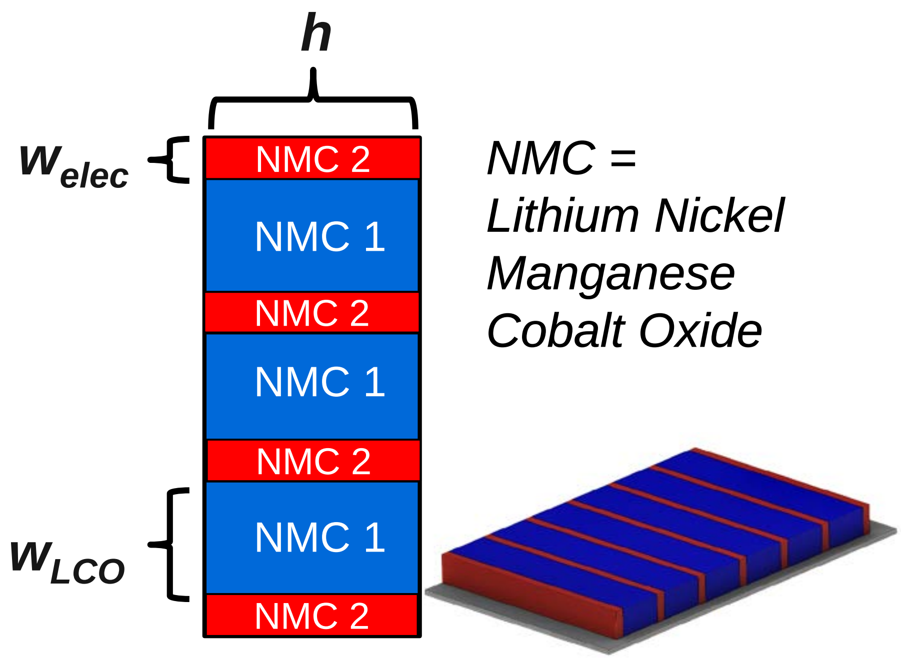
Source: **C.L. Cobb** and M. Blanco, *Journal of Power Sources*, Vol. 249, pp. 357-366, 2014.

Modeling Summary

- Pure (100%) electrolyte channels enhance lithium utilization in thick cathodes but impact the total capacity
- Additional modeling is being conducted on structures with higher porosity material in the 'electrolyte' regions to reduce total capacity impact



CoEx Structure 1
(modeled)



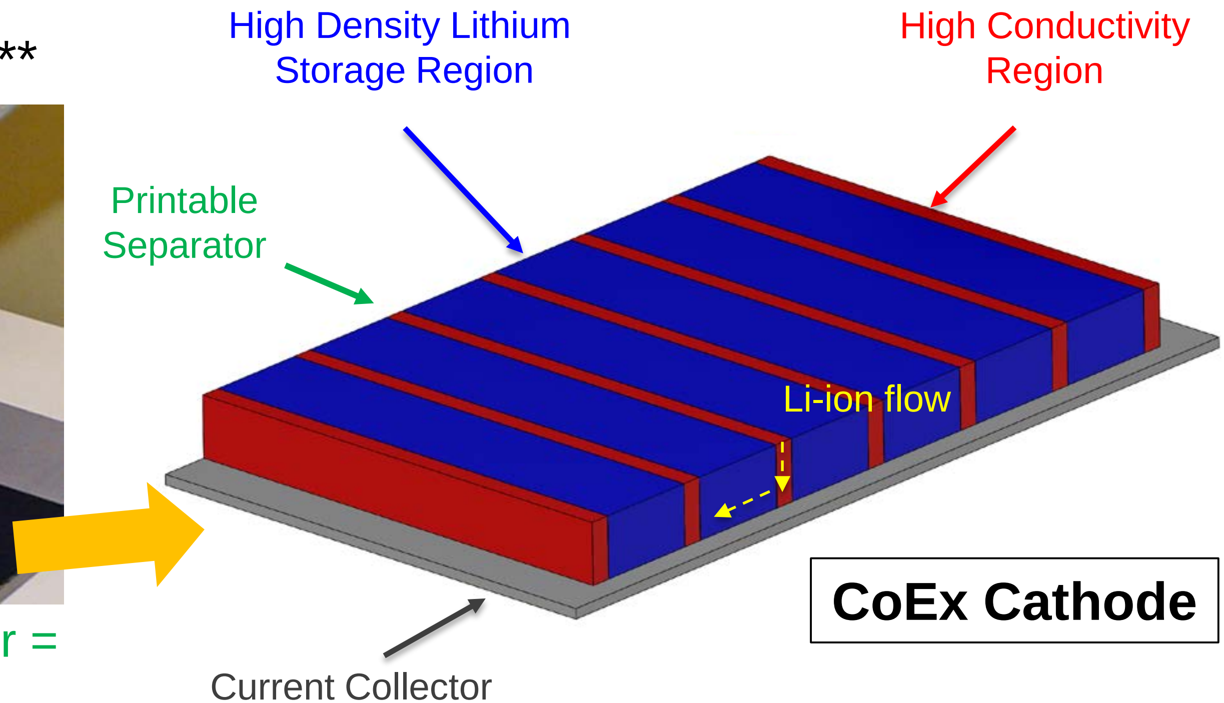
CoEx Structure 2
(switch to NMC for ARPA-E funded project)

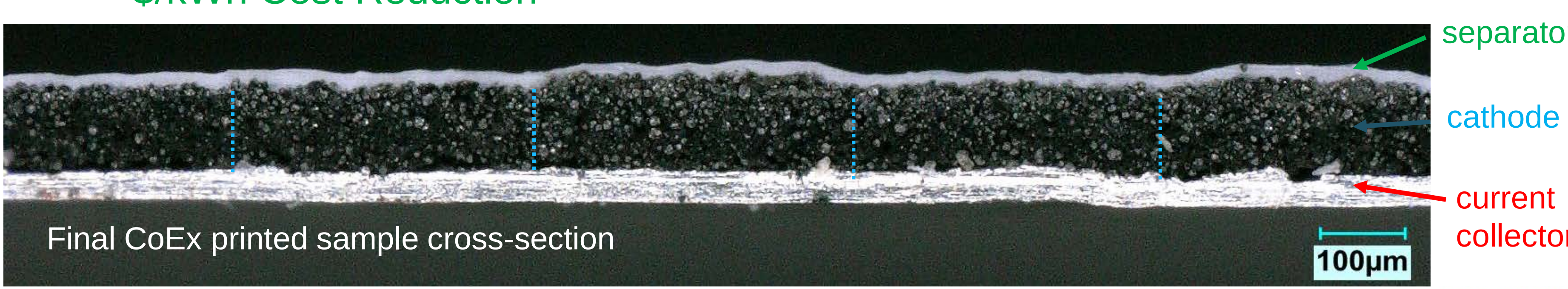
CoEx Batteries: Making it Work

(In collaboration with Lawrence Berkeley National Laboratory)

Co-extrusion Printhead**

CoEx + Printable Separator = $/kWh Cost Reduction



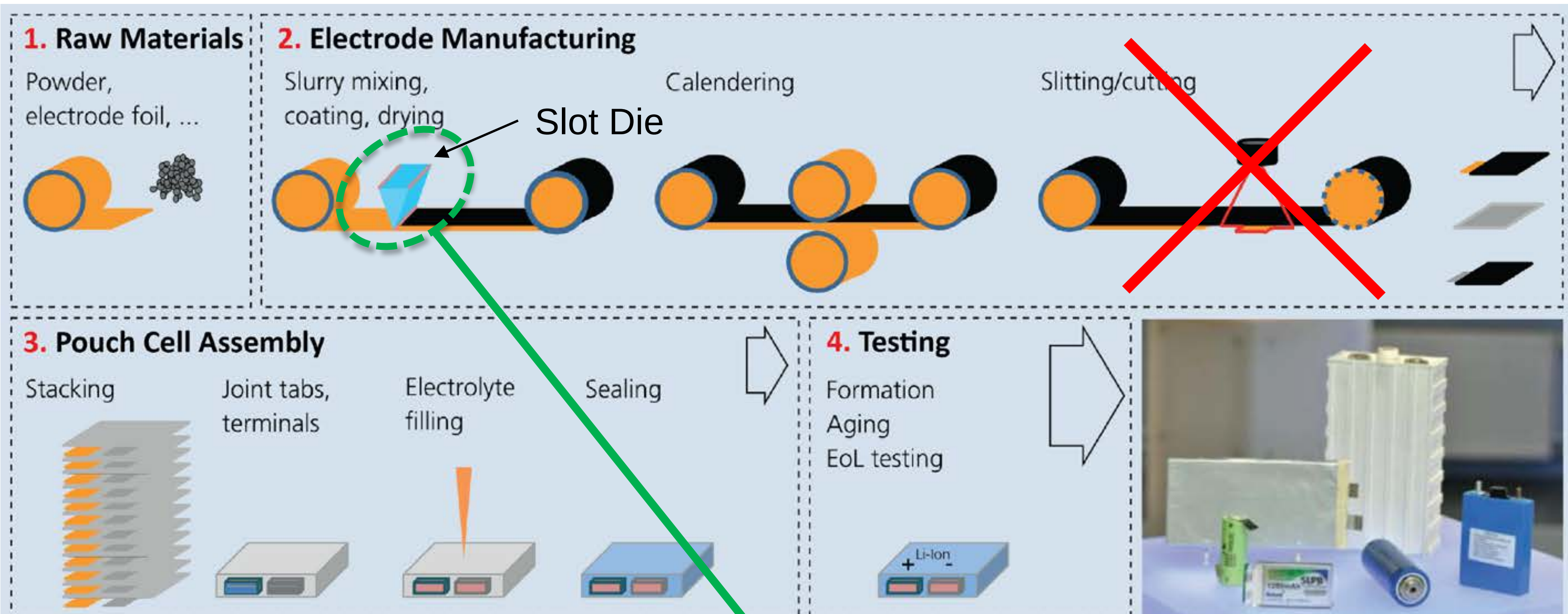


Final CoEx printed sample cross-section

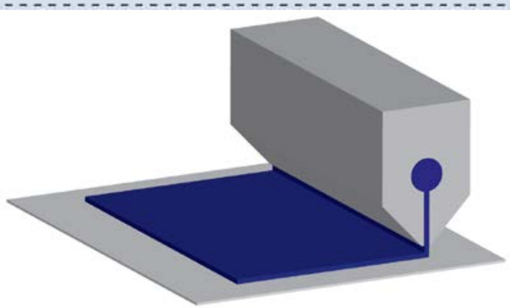
**Funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000324*

Lithium-Ion Battery Manufacturing

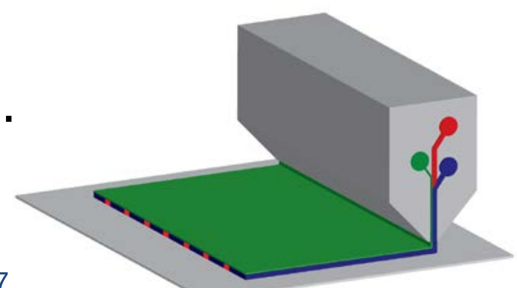
ARPA-E Impact: Potential ~**10-15% reduction in $/kWh costs** through the elimination of process steps with a printable separator



Conventional
One material



vs.



Co-Extrusion
(CoEx)
Multiple Materials

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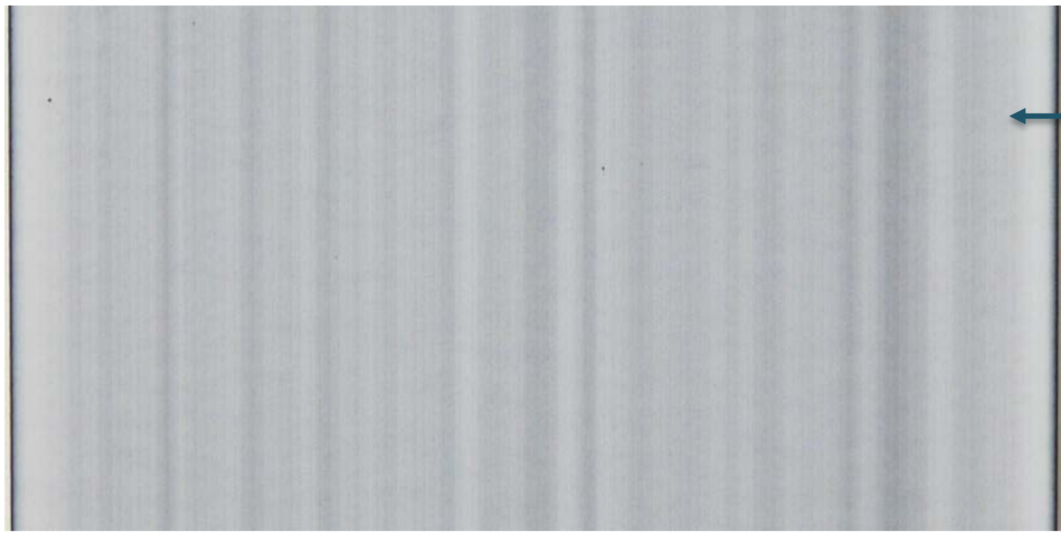
Image Source: Fraunhofer IKTS Annual Report 2012-2013

CoEx Print Cross-Section

Heterogeneous cathode and separator print where the dried separator layer ranged from **16 to 21** µm



Cross-section view of dried, uncalendered print

Data courtesy of S. Solberg

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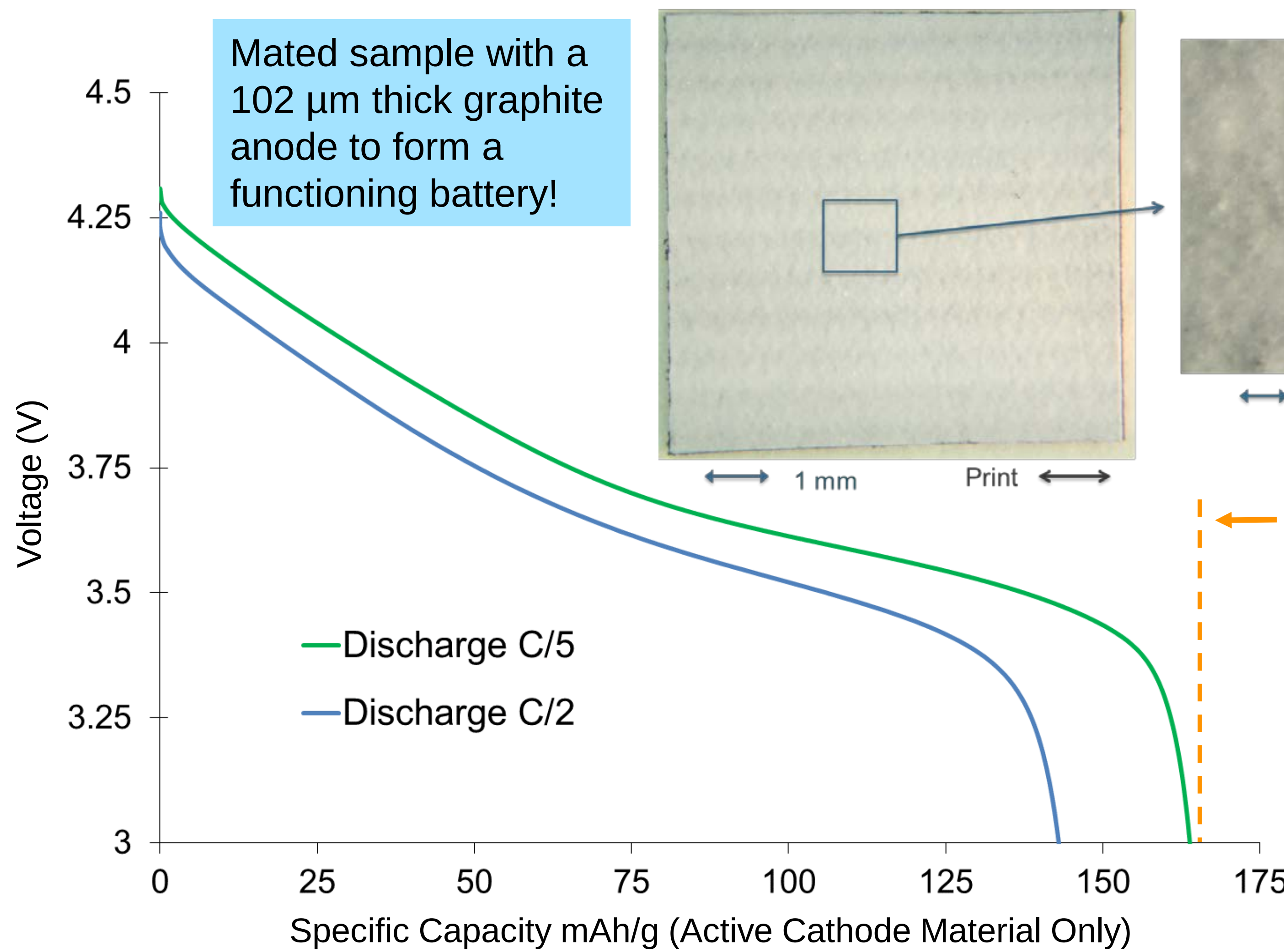
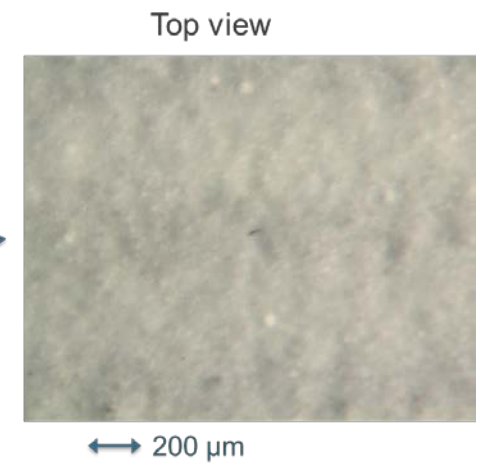
Electrochemical Test Results

Mated sample with a 102 µm thick graphite anode to form a functioning battery!





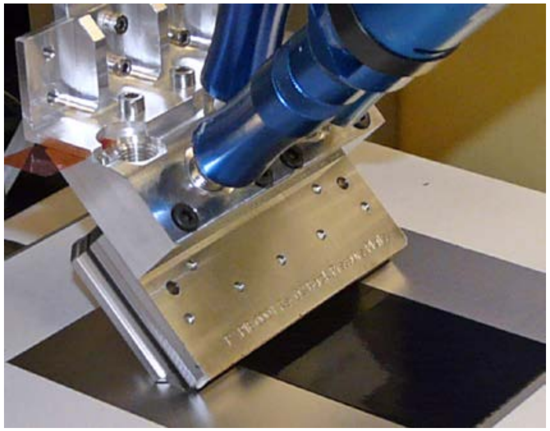
165 mAh/g
(Max theoretical for NMC chemistry)

<u>Current Research</u>: Optimize CoEx Cathode Performance

Data courtesy of S. Solberg & C. Bae

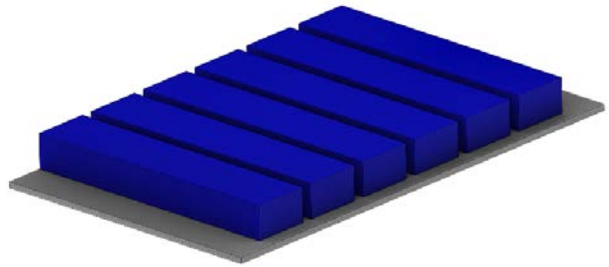
Co-Extrusion (CoEx): Advanced Manufacturing for Batteries

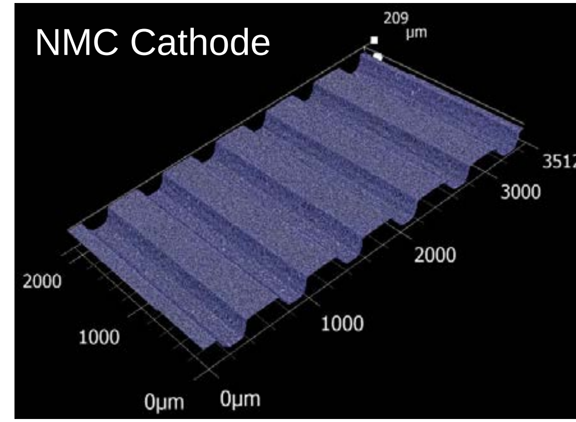
Co-extrusion Printhead



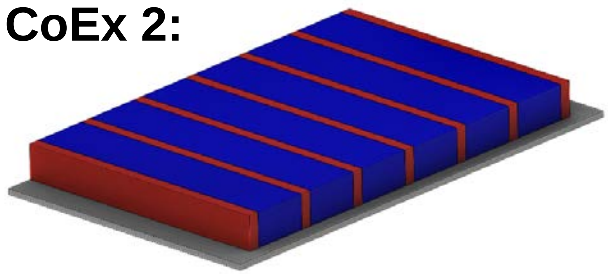
We are currently leveraging ARPA-E investment to optimize the CoEx cathode for Electric Vehicle (EV) applications

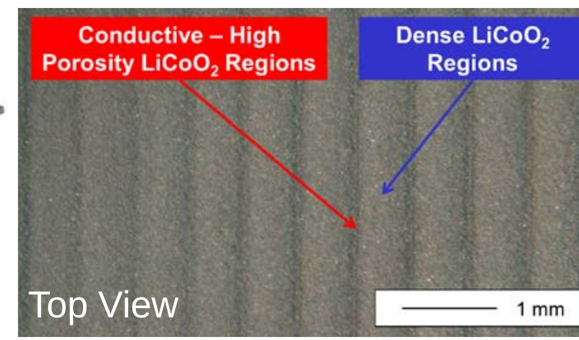
CoEx 1:



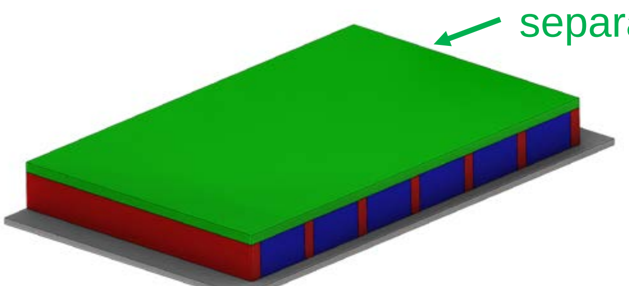


CoEx 2:





EERE, Award Number DE-EE0007303



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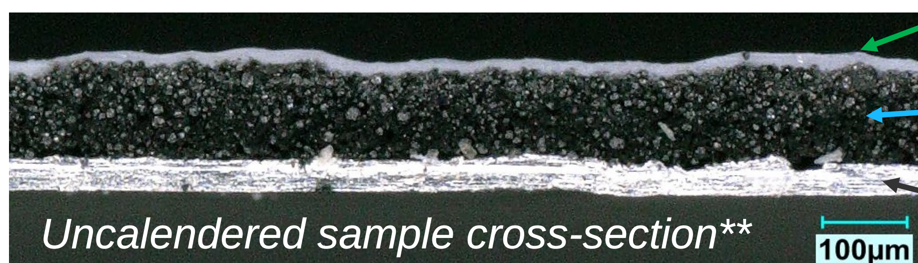
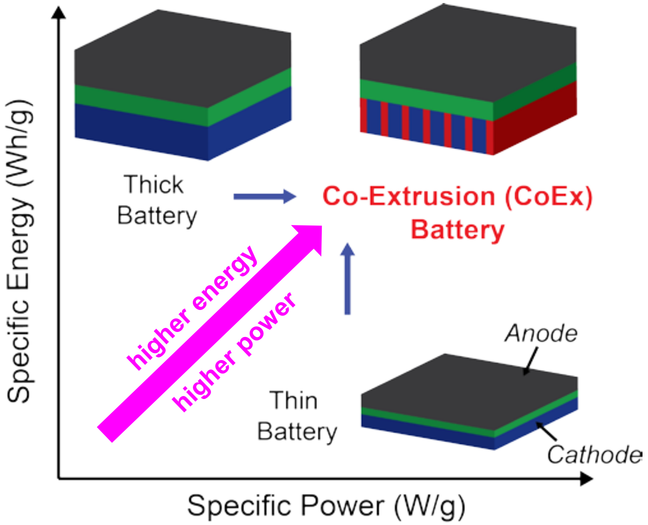
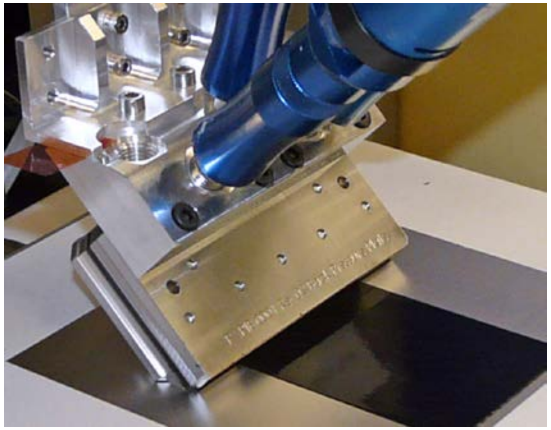


Conclusions

- Modeling results estimate a >15% improvement in gravimetric capacity
- Successfully fabricated a separator and a heterogeneous cathode in a single pass with a path towards an ~15% reduction in $/kWh costs
- <u>Current Research:</u>
    - Partnered with Ford and Oak Ridge National Lab on $3M award to optimize and implement the CoEx cathode technology for EV pouch cells (Contract No. DE-EE0007303)





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  - Dr. Venkat Srinivasan
  - Dr. Shao-Ling Wu
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  - Dr. Mario Blanco

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