Bottom-up design of electrodes for redox flow batteries

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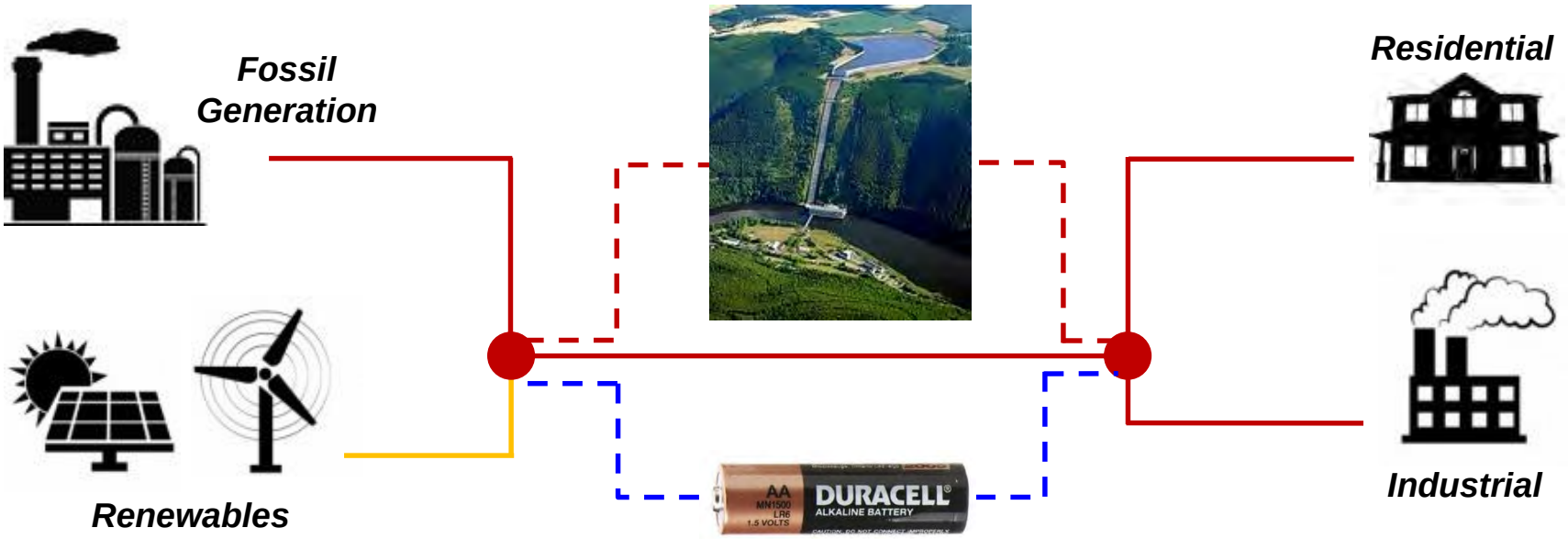
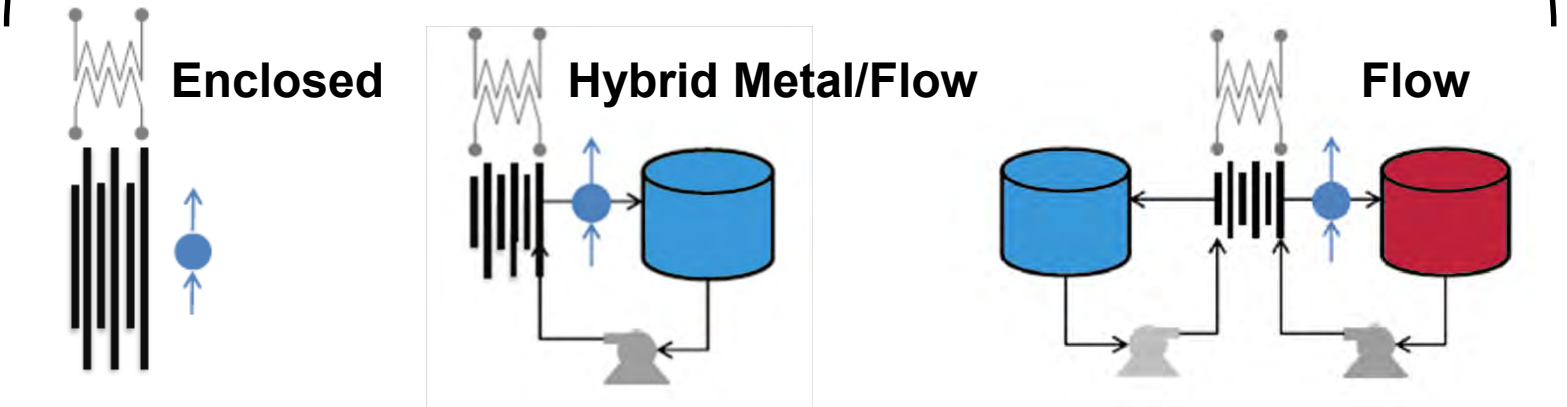
Grid Storage: From pumped-hydro to batteries

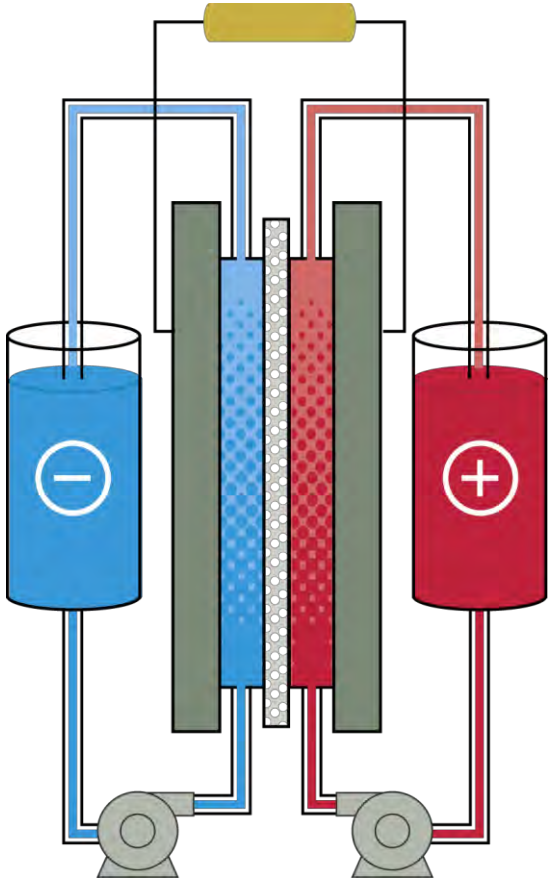


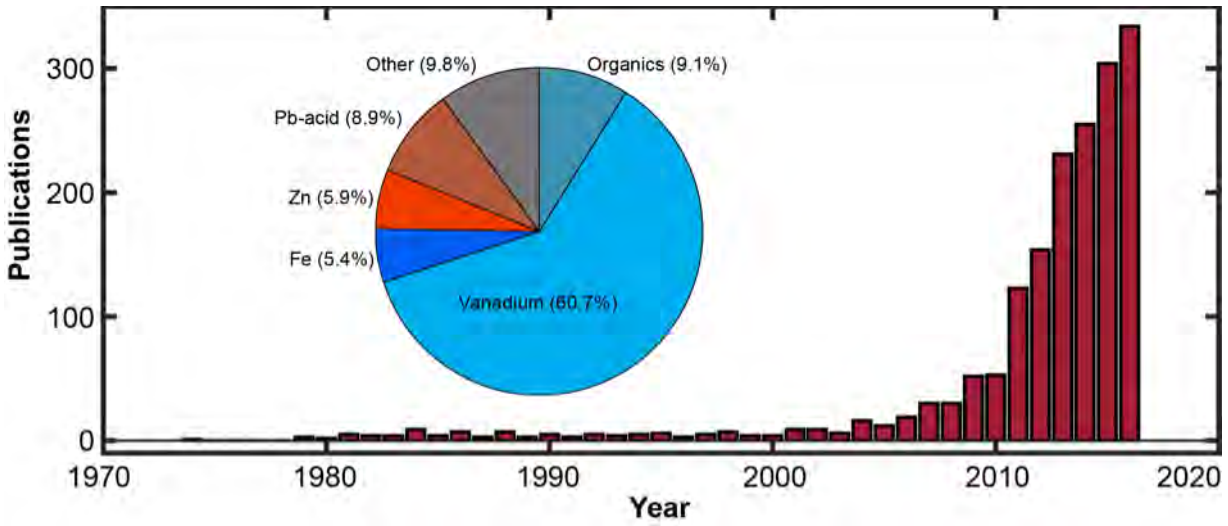


Price & lifetime are paramount to grid storage

DOE Global Energy Storage Database (2017). *www.instructables.com;* Wikipedia, US Department of Energy, Report on the First Quadrennial Technology Review, 2012

Redox flow batteries are a nascent technology



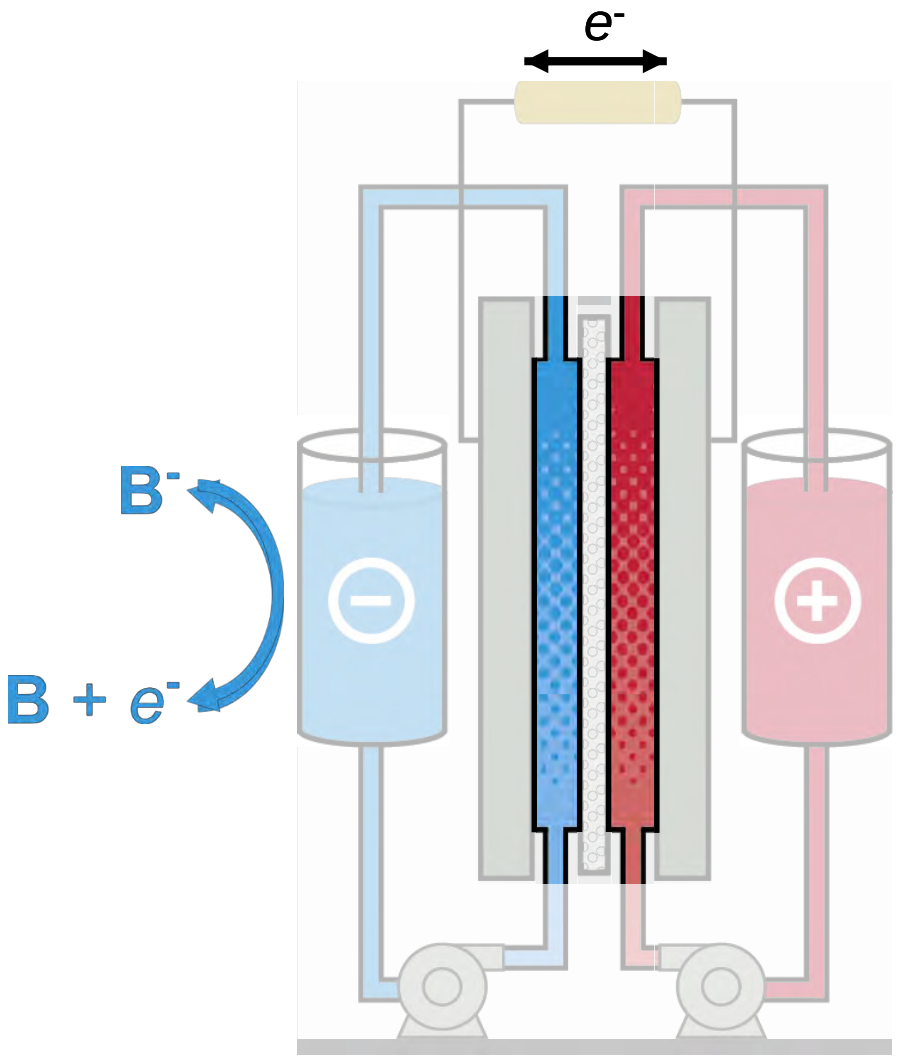


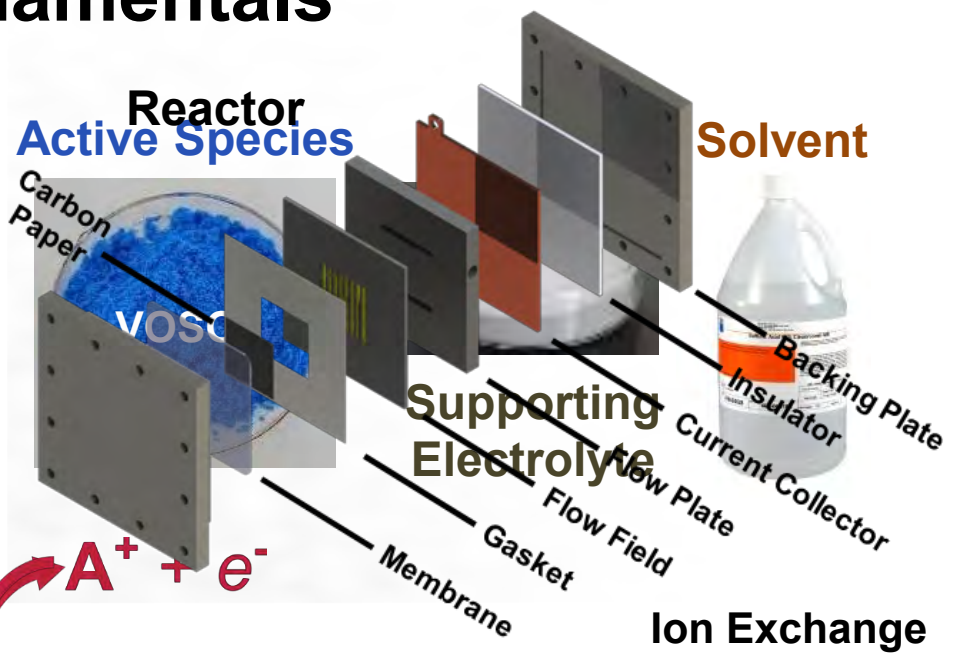
In 2014, RFB system costs exceeded $500 kWh^{-1}, well above the $150 kWh^{-1} target set forth by the U.S. Dept. of Energy.

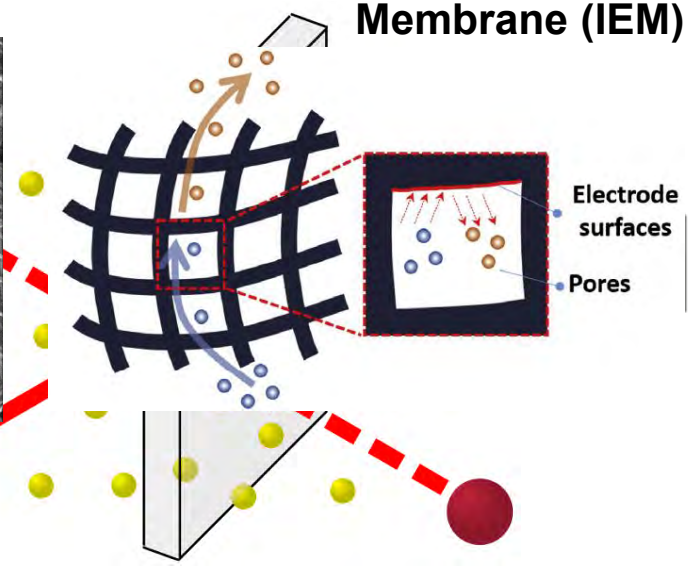
Opportunities for transformational technology advancement through the development of new redox chemistries and reactor designs.

Publication data based on a keyword search using Scopus to quantify the number of publications for each topic
Gyuk, US DOE Program Planning Document (2011). Darling & Gallagher et al., *Energy Environ. Sci.*, 2014, 7, 3459.

Redox flow battery fundamentals

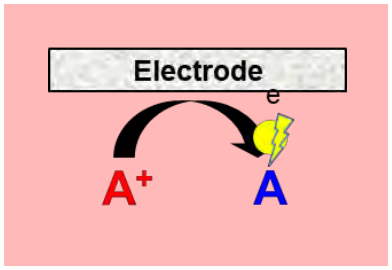


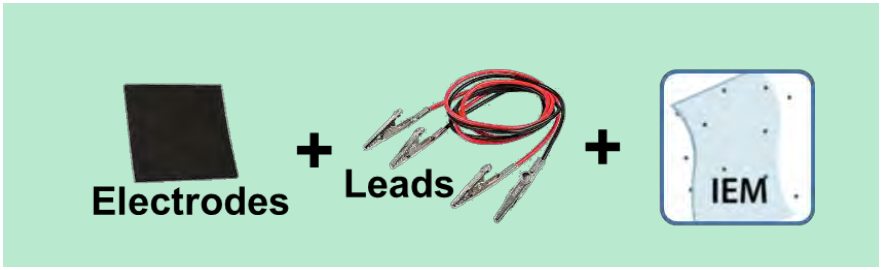


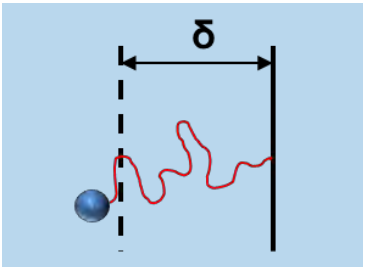


Su et al., in *Rechargeable Batteries*, Springer, (2015) 673. Zhou et al., J. Power Sources., 339 (2017) 1. Rashpov et al., J. Electrochem. Soc., 162 (2015) F603. Gyuk, US DOE Program Planning Document (2011). Darling et al., Energy Environ. Sci., 7 (2014) 3459.

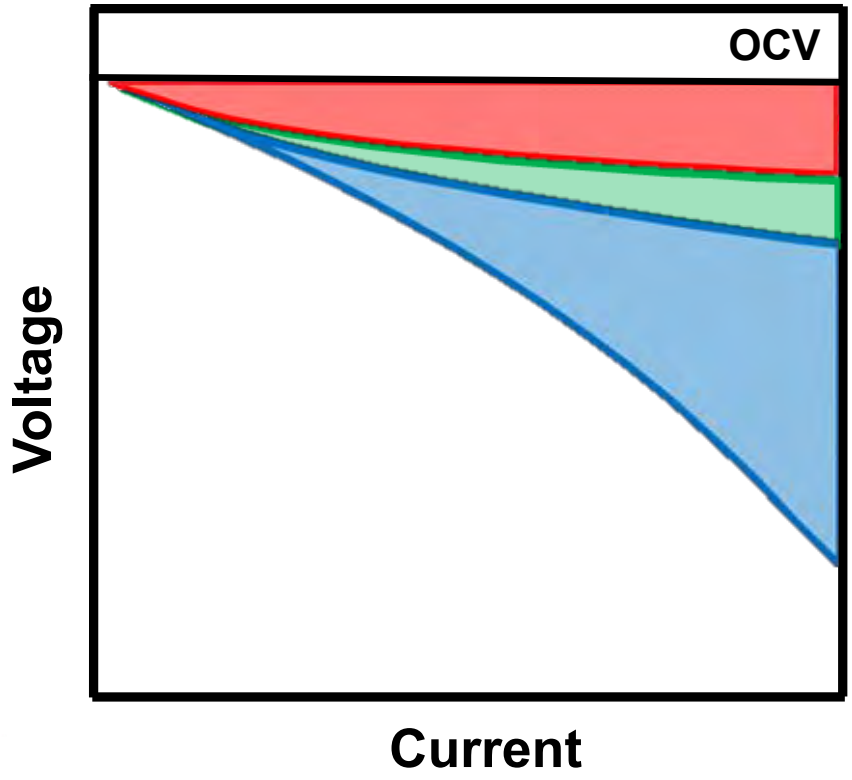
Electrodes are central to RFB performance





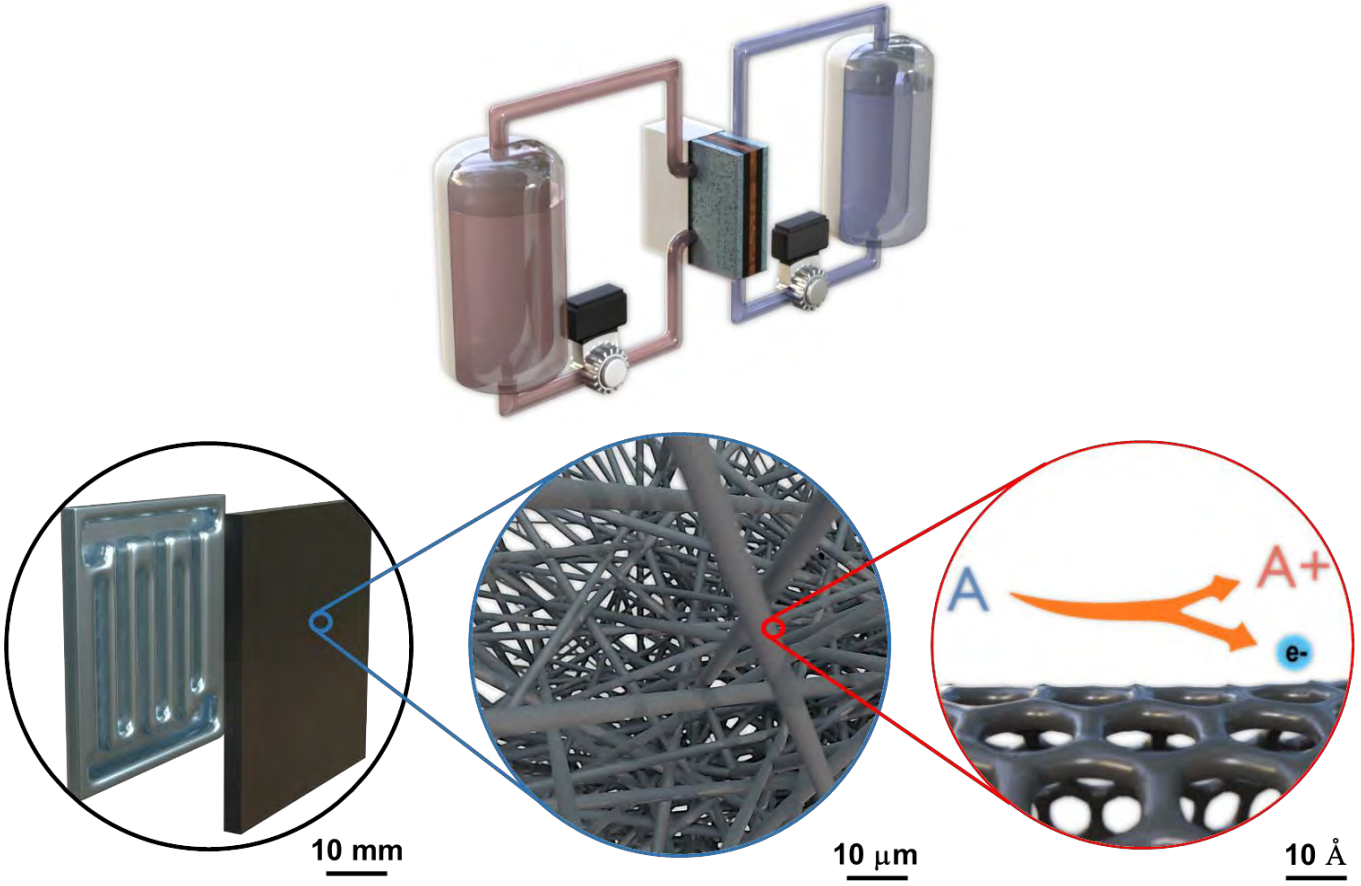


Performance losses – polarization curve



$$E_{cell} = OCV - \eta_{act} - \eta_{ohm} - \eta_{conc}$$

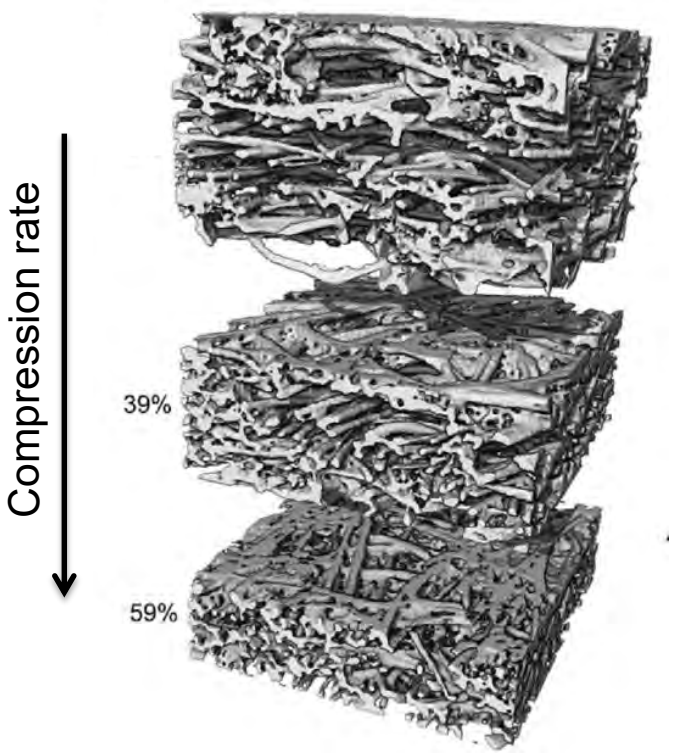
Understanding electrodes at multiple length scales



Minimizing area-specific resistance is a powerful strategy for reducing reactor cost contributions to the total system cost

Forner-Cuenca & Brushett., *Current Opinion in Electrochemistry*, 18, 113 (2019)

Developing advanced electrodes requires tailoring of <u>microstructure</u> & <u>surface chemistry</u>

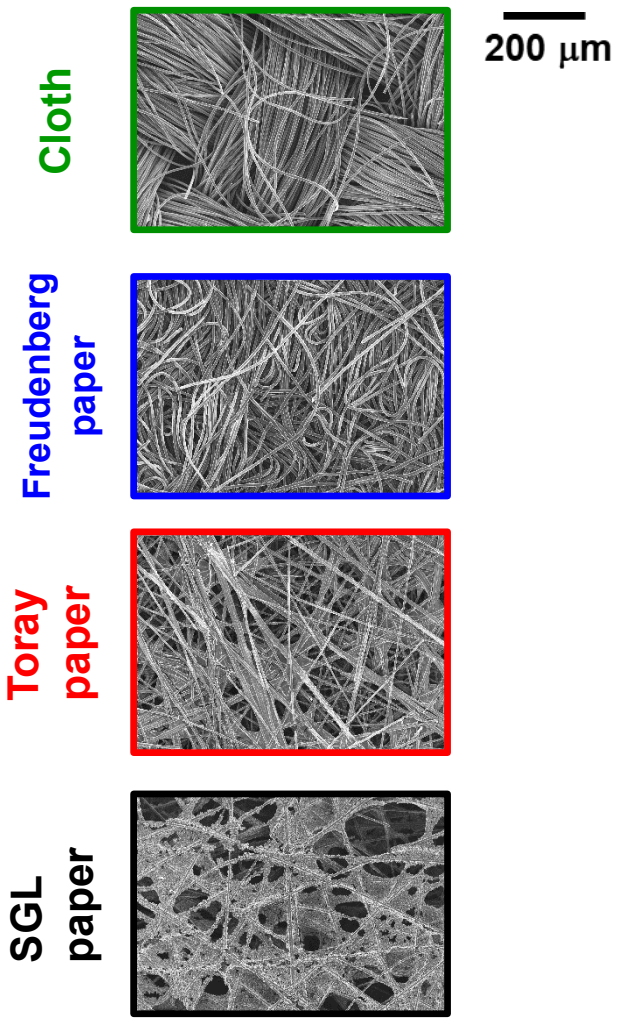


Microstructure

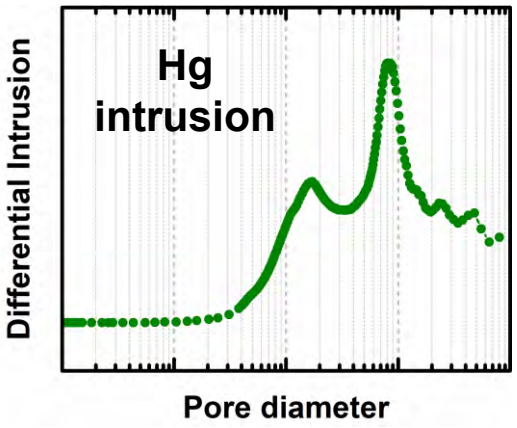
Surface properties

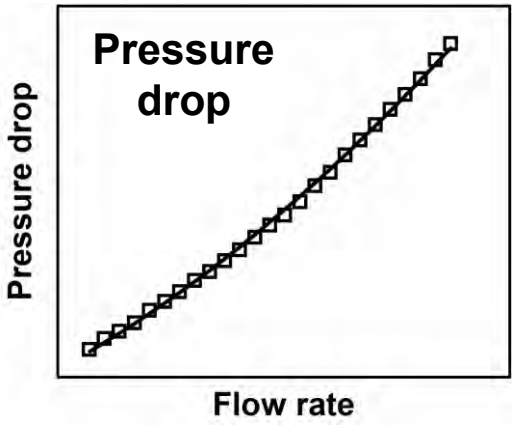
Zenyuk et al. *J. Power Sources.*, 2016, **328**, 364

How does microstructure impact performance?



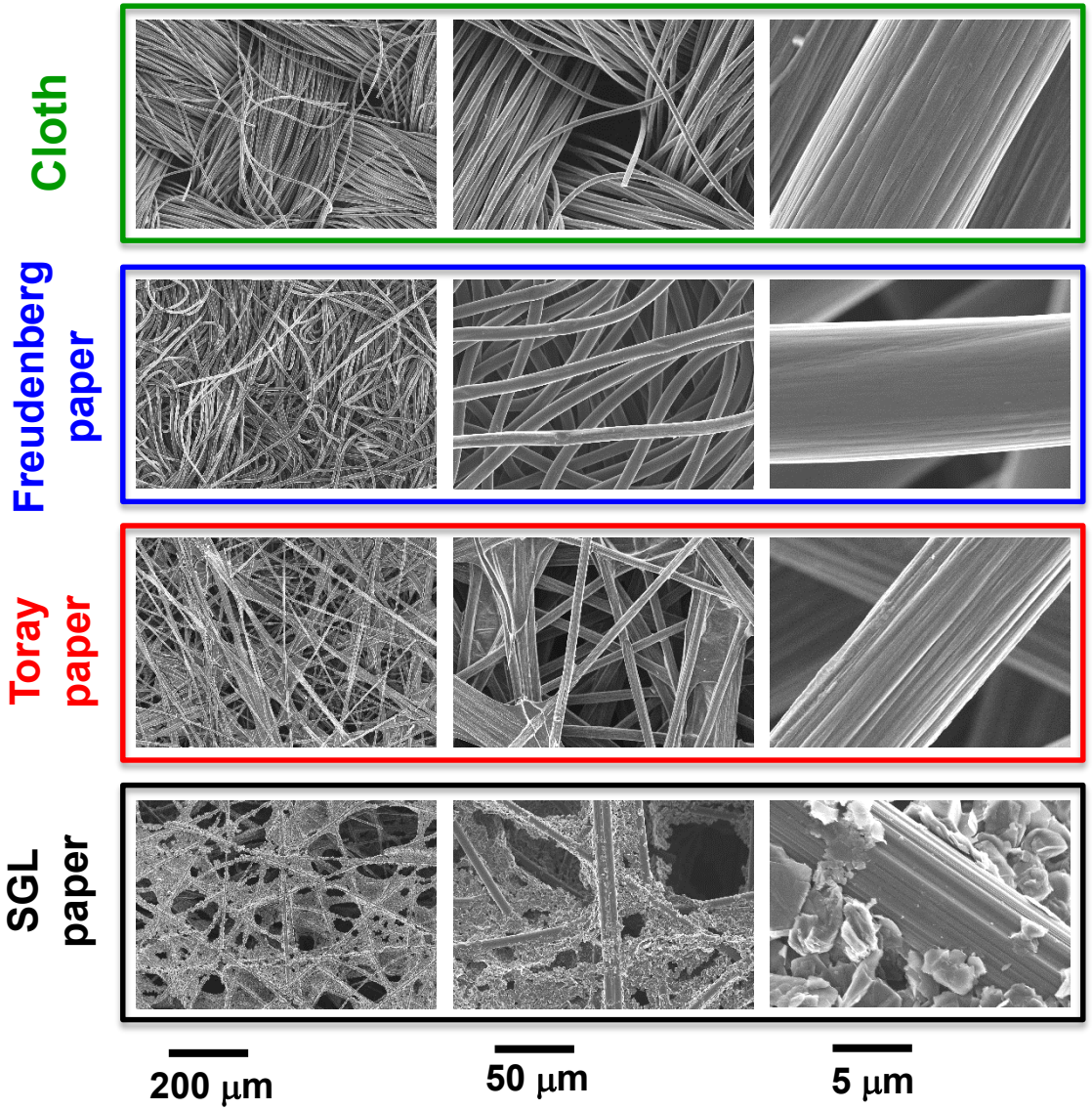
Microstructure Characterization

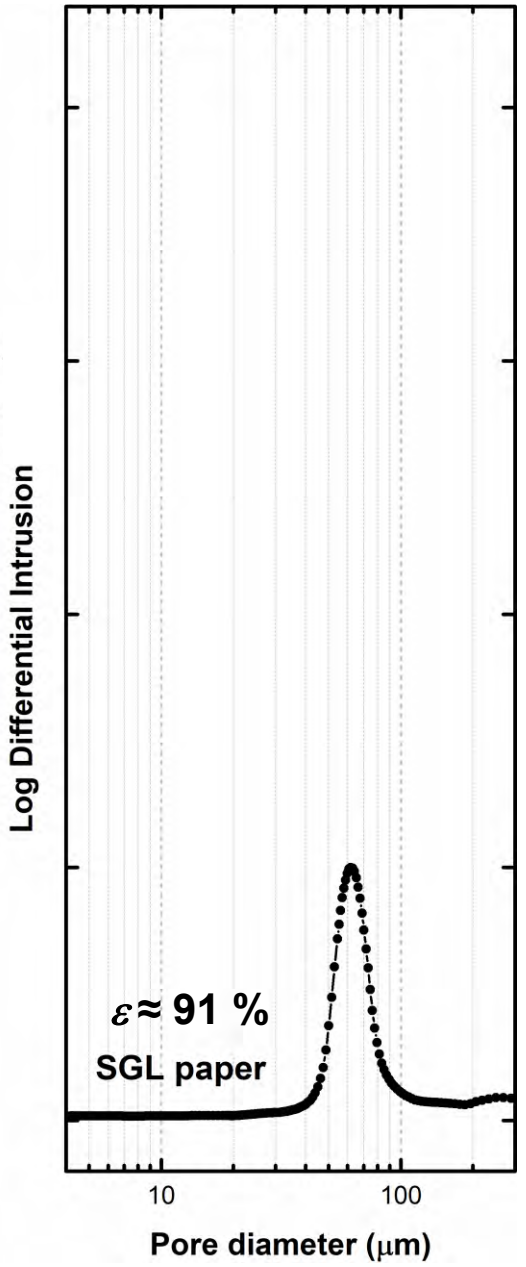




Electrochemical Characterization

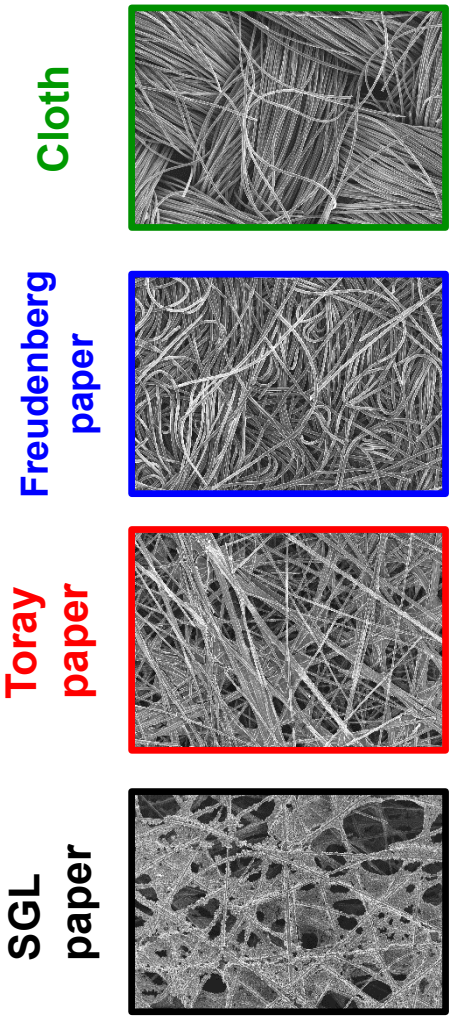
Electrode microstructure

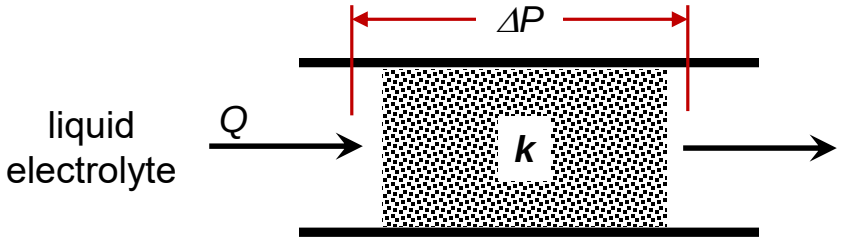




Forner-Cuenca et al., *Journal of The Electrochemical Society*, 166(10) A2230-A2241 (2019)

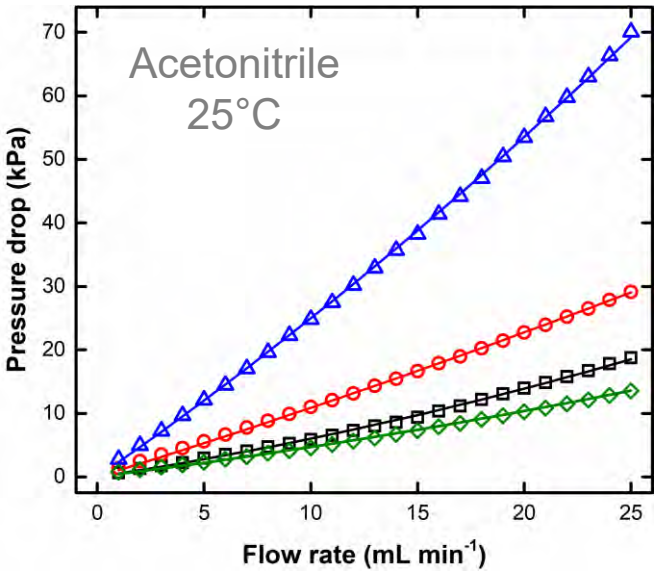
Lower pressure drop reduces parasitic losses

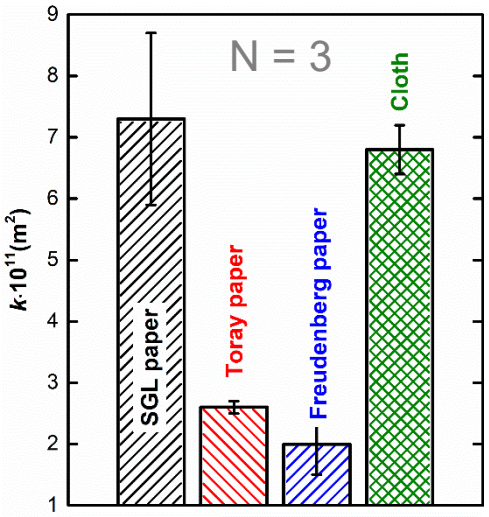




$$-\frac{dP}{dx} = \frac{\mu v}{\boldsymbol{k}} + \beta\rho v^2 \qquad Re = \frac{\boldsymbol{k}\beta\rho v}{\mu}$$

Darcy-Forchheimer Law

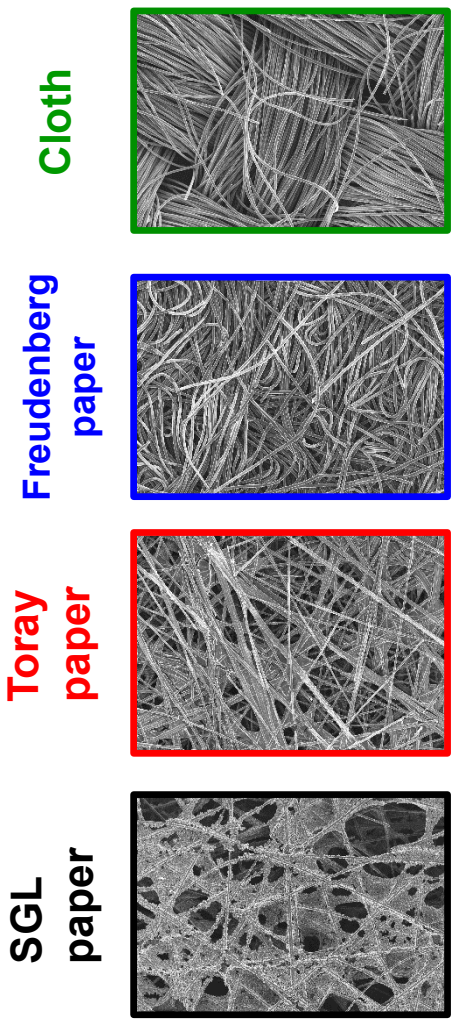




High permeability means lower pressure drop (less pumping losses)

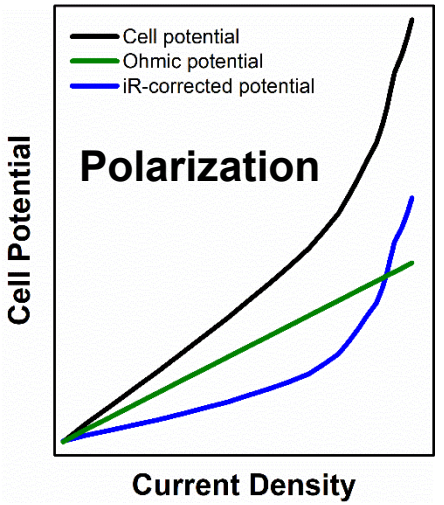
Forner-Cuenca et al., *Journal of The Electrochemical Society*, 166(10) A2230-A2241 (2019)

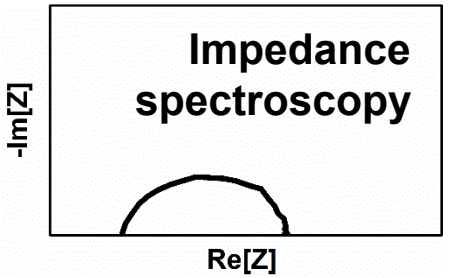
How does microstructure impact performance?



Microstructure Characterization

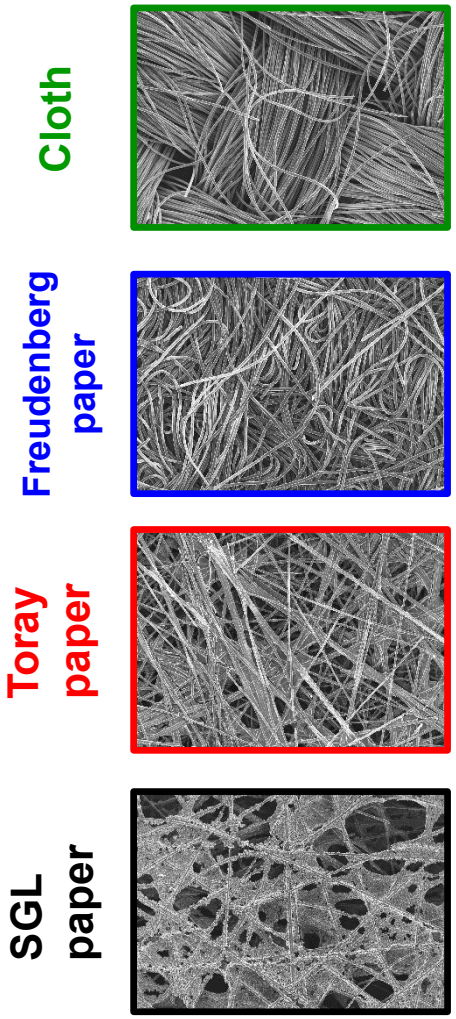
Electrochemical Characterization

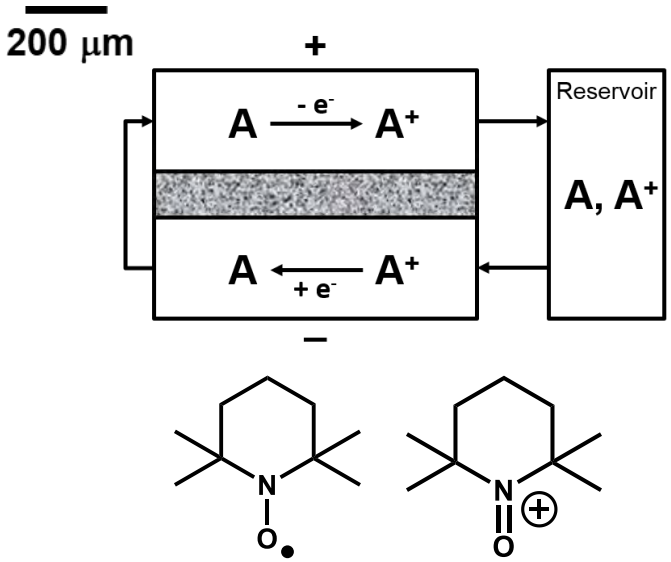


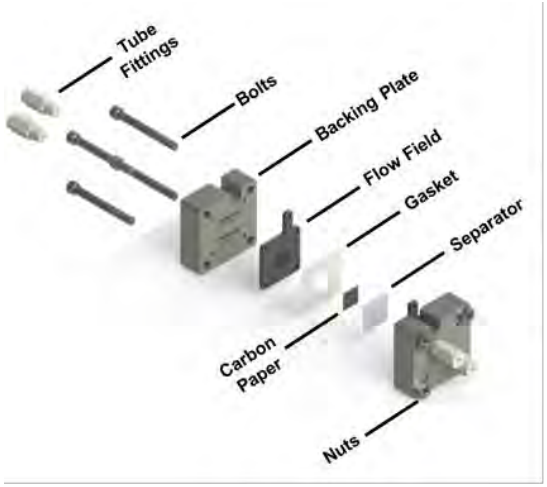


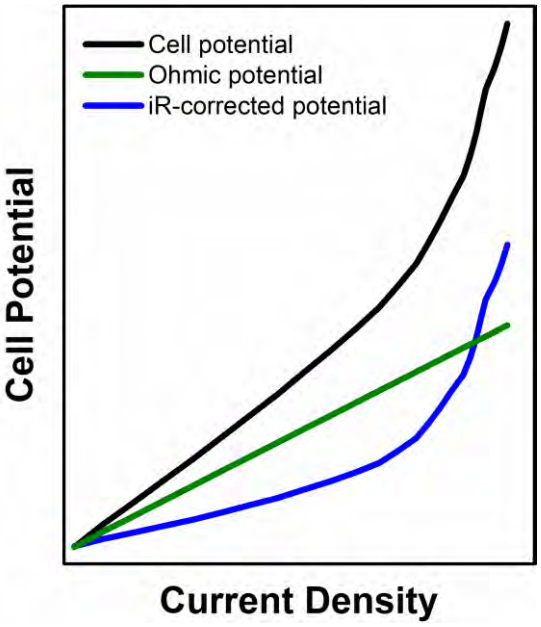
Forner-Cuenca et al., *Journal of The Electrochemical Society*, 166(10) A2230-A2241 (2019)

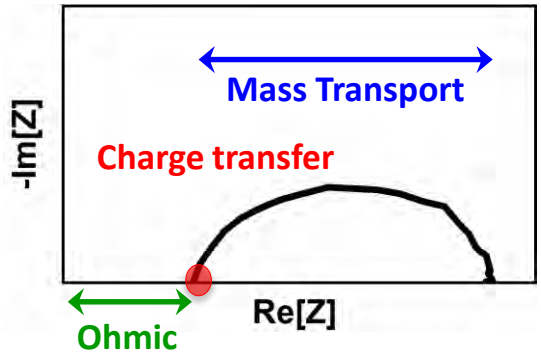
Leveraging flow cells as analytical platforms





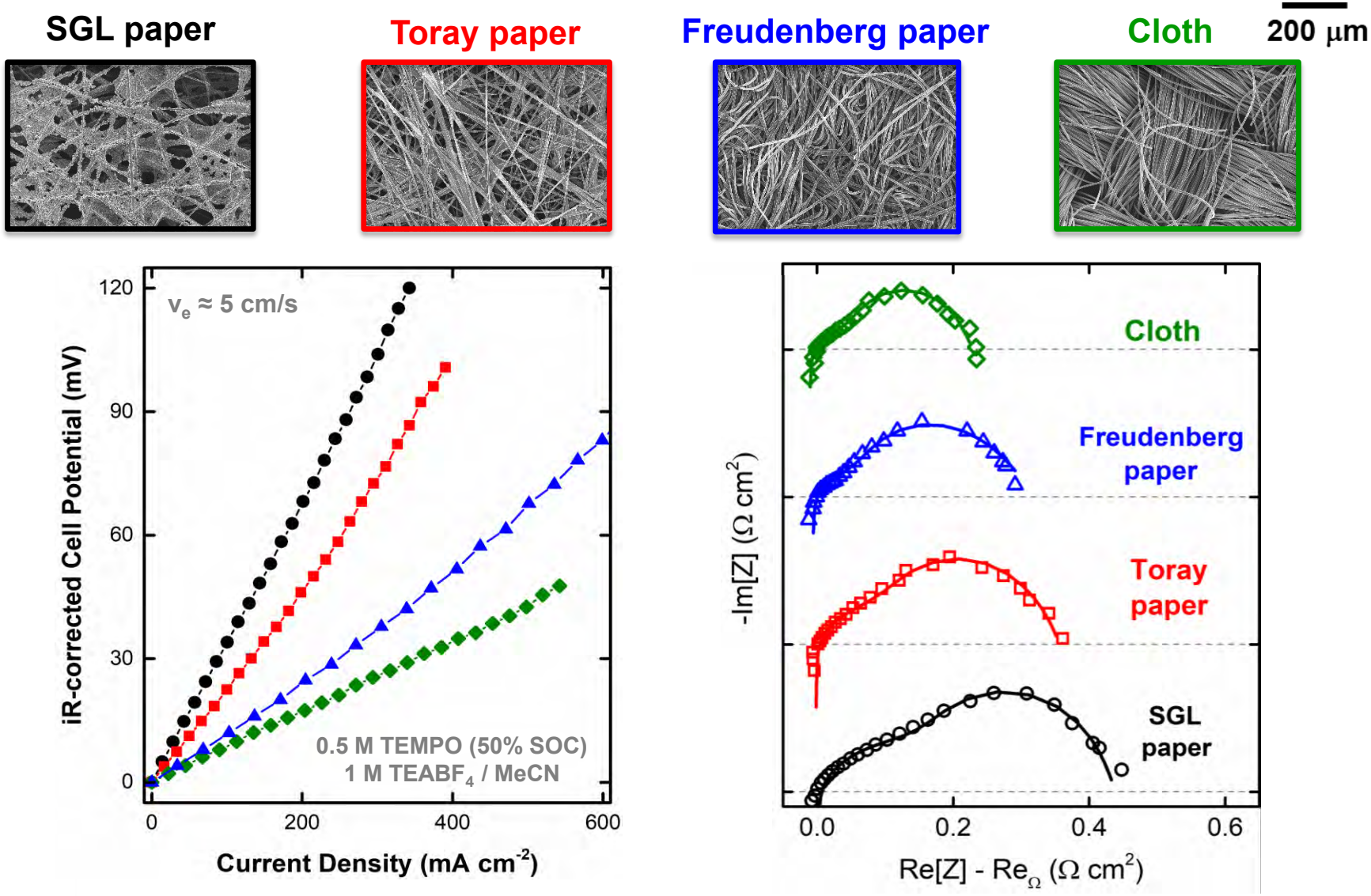






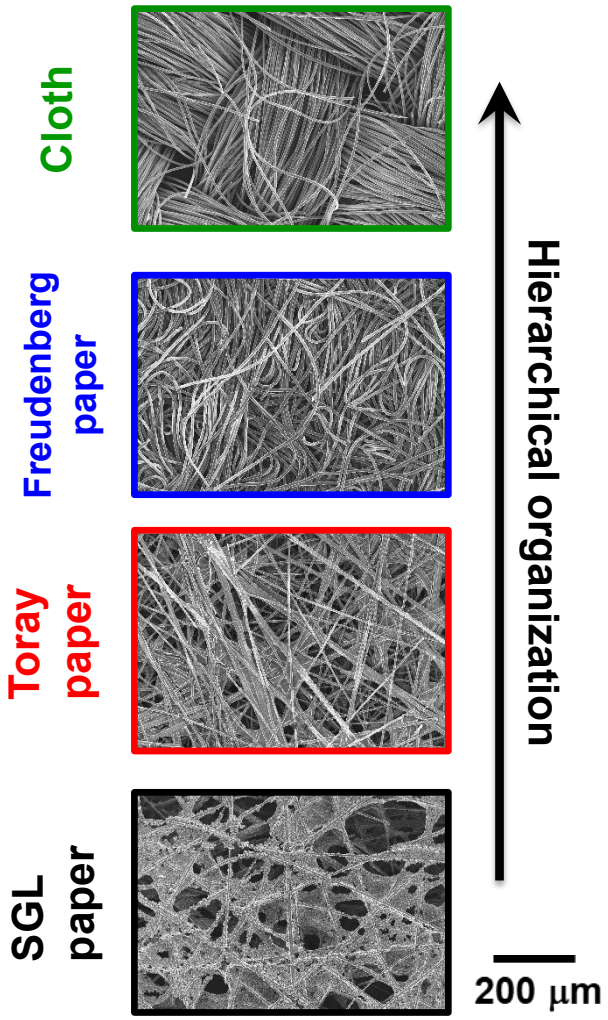
Milshtein & Kaur et al., *Energy Environ. Sci*. 2016, 9, 3531; Forner-Cuenca et al., *Journal of The Electrochemical Society*, 166(10) A2230-A2241 (2019)

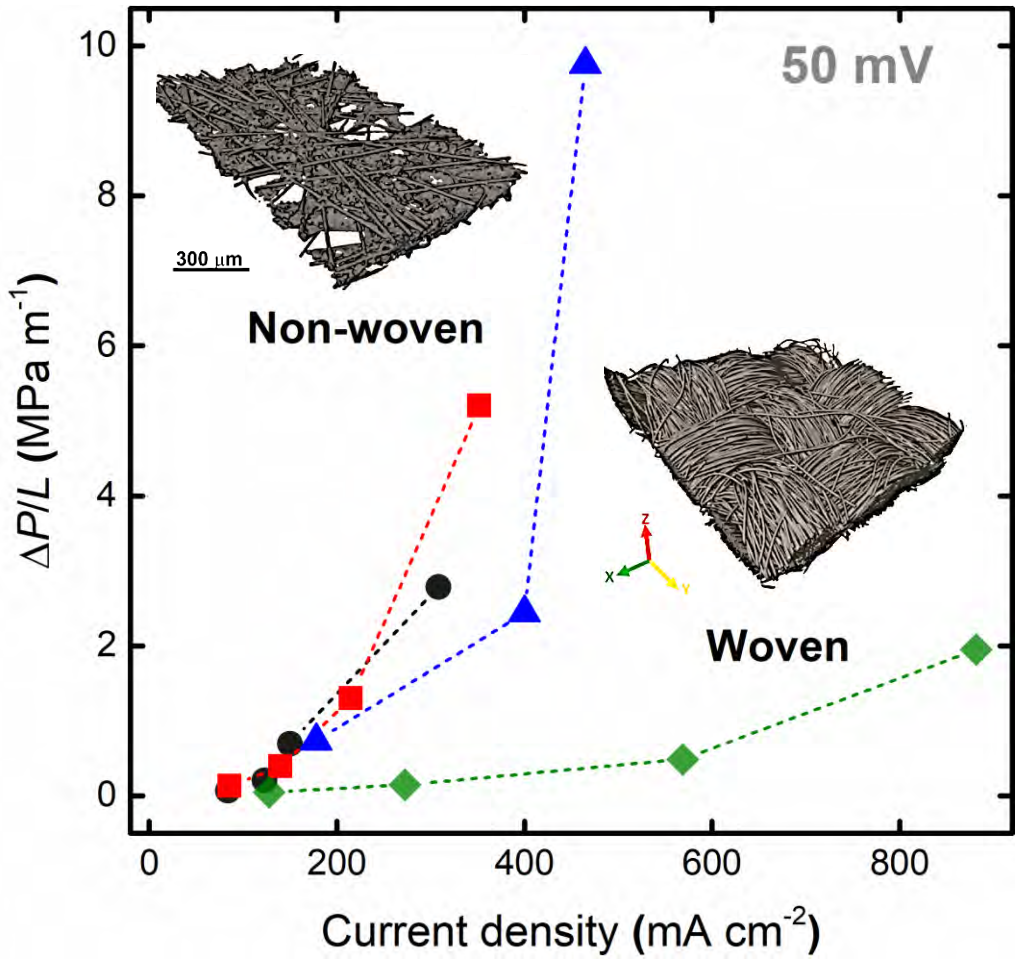
Electrode microstructure governs mass transport



Forner-Cuenca et al., *Journal of The Electrochemical Society*, 166(10) A2230-A2241 (2019)

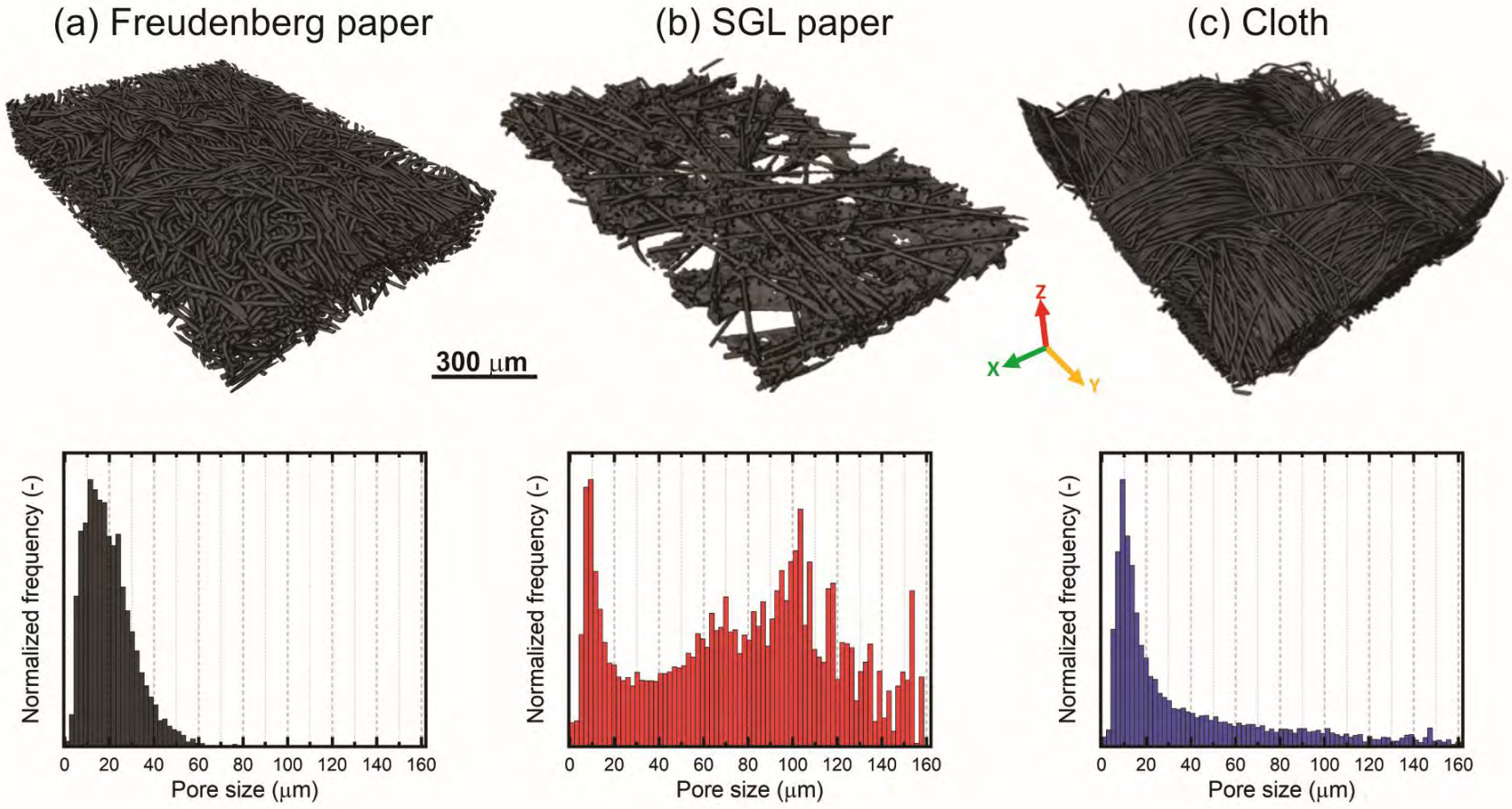
Electrode structuring improves mass transfer





Forner-Cuenca et al., *Journal of The Electrochemical Society*, 166(10) A2230-A2241 (2019)

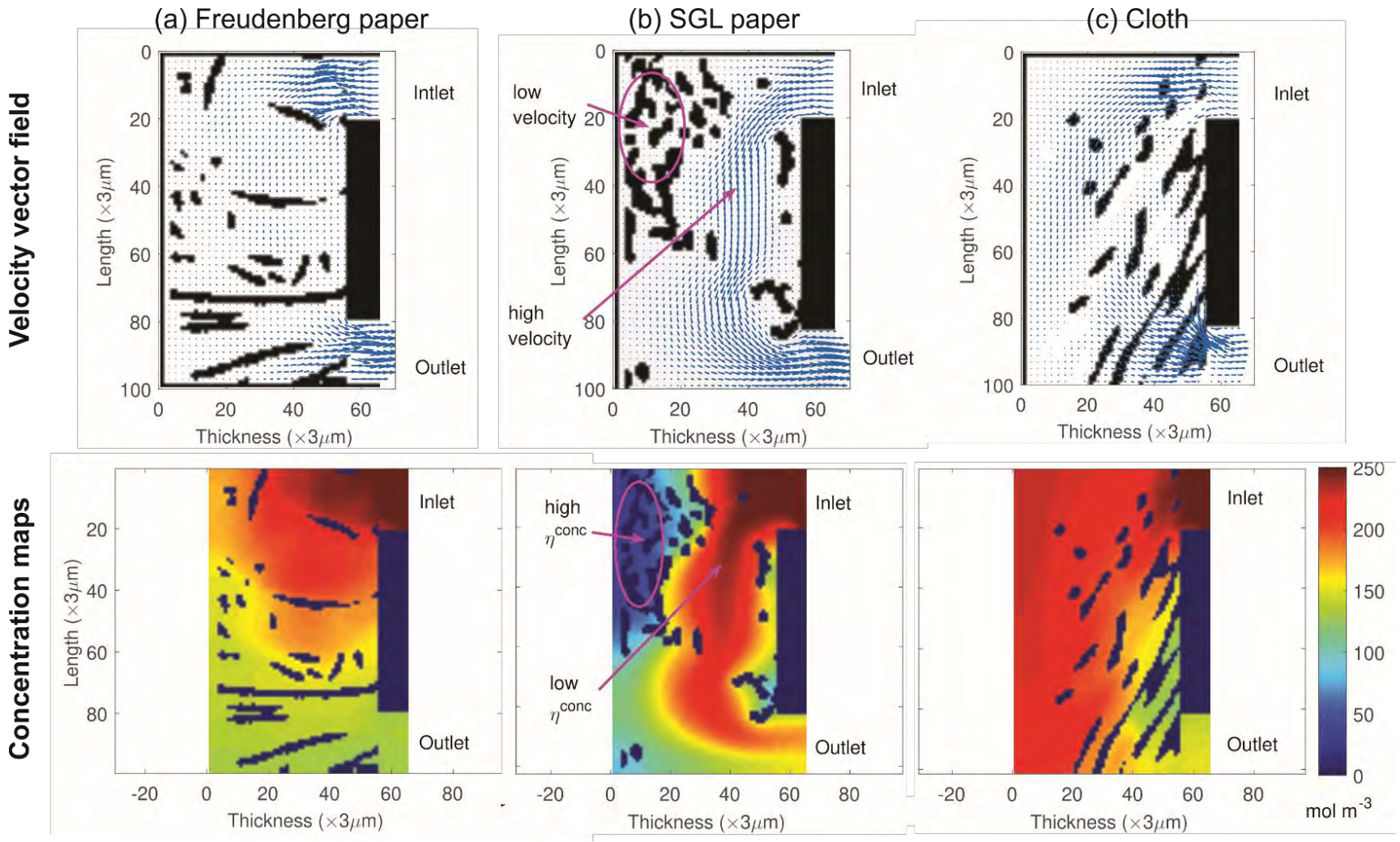
Microstructure-informed modelling is needed for detailed understanding



X-ray tomographic images as input for a Lattice-Boltzmann model

Zhang and Forner-Cuenca et al., *Journal of Power Sources* 447 (2020) 227249

Microstructural organization reduces mass transfer overpotential

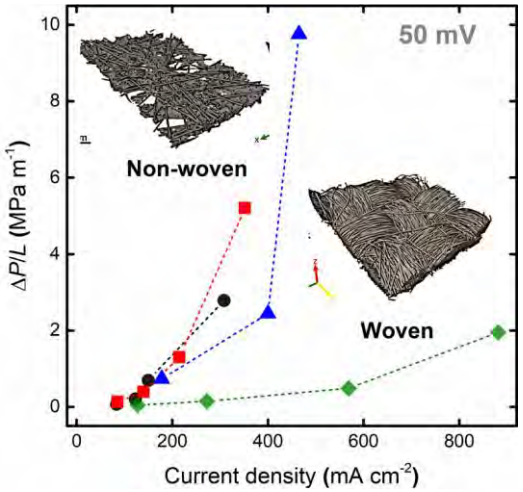


Zhang and Forner-Cuenca et al., *Journal of Power Sources* 447 (2020) 227249

Take-home messages

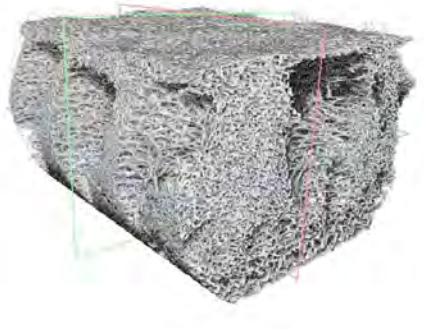
- Redox flow batteries (RFBs) are a nascent but promising technology but further cost reduction are needed for ubiquitous adoption

- Diagnostic flow cell platforms, coupled with *ex-situ* characterization and porous electrode modeling, can enable detailed analysis of electrode performance



- Electrodes featuring bimodal pore size distribution (i.e. carbon cloth) provide excellent electrochemical performance and low pressure loss

- Bottom-up synthesis of electrodes using phase separation of polymer solutions is a promising and facile method to control the 3D structure of the electrode



Thanks for your attention!

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