Advanced Vehicle Engineering Centre

How accurate is state of charge as a predictor of remaining useful work in lithium sulfur batteries?

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www.cranfield.ac.uk/djauger

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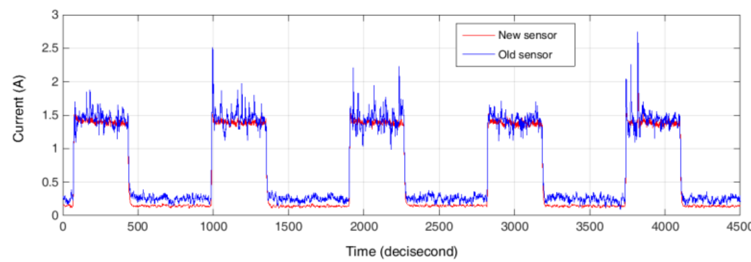
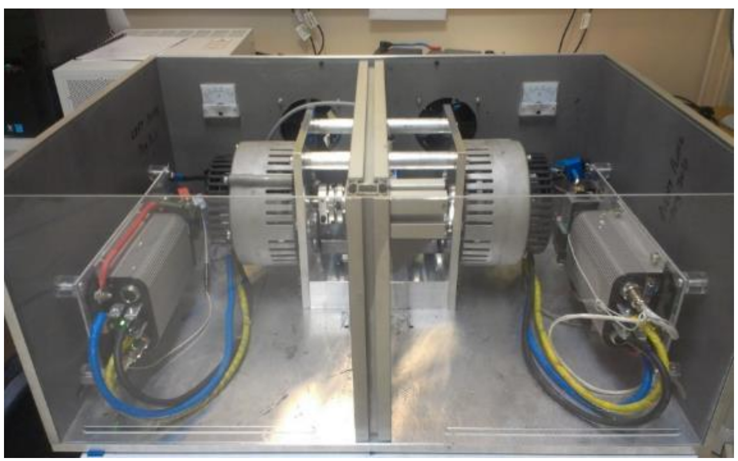
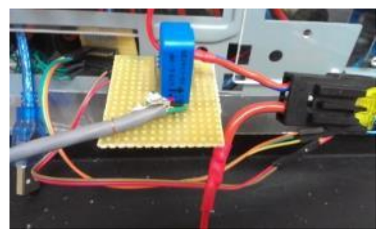
What My Team Does: Application Prototyping

- Rapid control prototyping
- Battery HIL testing
- Duty cycle simulation in real-time
- Testing BMS software against real noisy measurement inputs

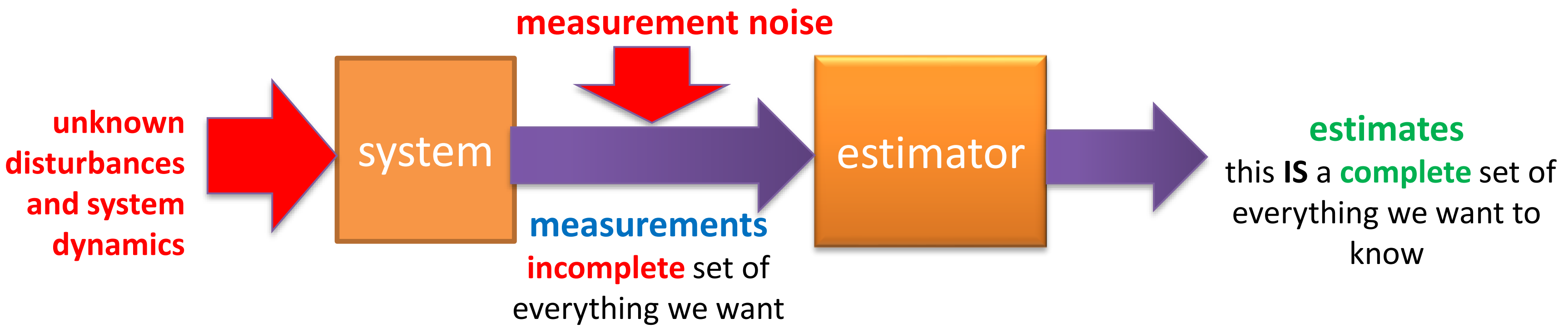






Practicable sensors → Good for evaluating the proposed algorithms in a challenging situation

What My Team Does: State Estimation for BMS Algorithms



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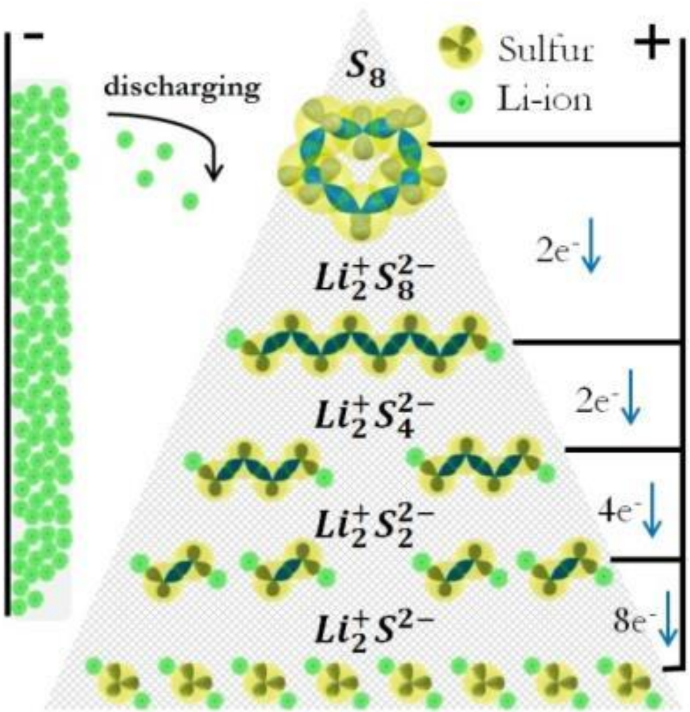
General Challenges in State Estimation in Lithium Sulfur Batteries



Propp et al, doi: 10.1016/j.jpowsour.2016.07.090

- The reactions in lithium-sulfur are complex.
- Electrochemical process has multiple stages.
- Different parts of the reaction may occur simultaneously in a cell.

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General Challenges in State Estimation in Lithium Sulfur Batteries

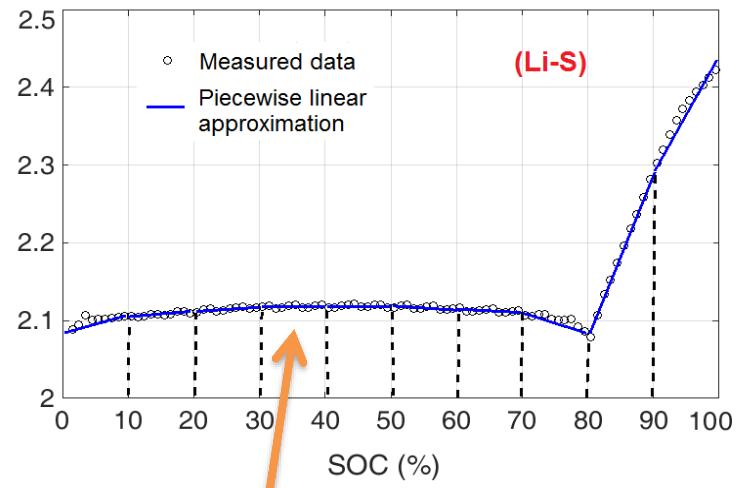
no coulomb counting

$$Q_{\text{rem}} = Q_{\text{init}} - \int_0^t i(\tau)\, d\tau$$

Two problems with this equation:

- Capacity depends on usage
- Self-discharge occurs

unhelpful OCV curve



Flat ‘low plateau’ makes it impossible to estimate remaining capacity from open-circuit voltage alone.

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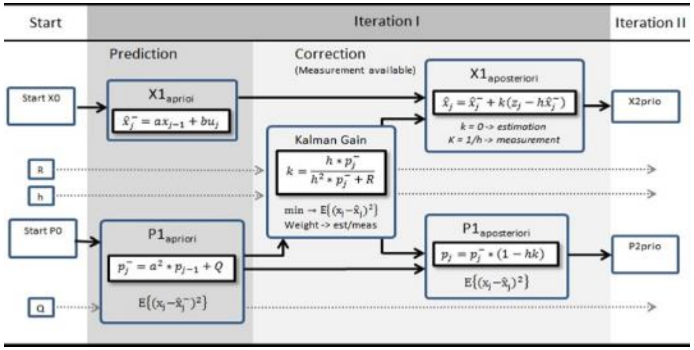
Techniques for State Estimation in Lithium-Sulfur Batteries

Technique 1: From Control Theory

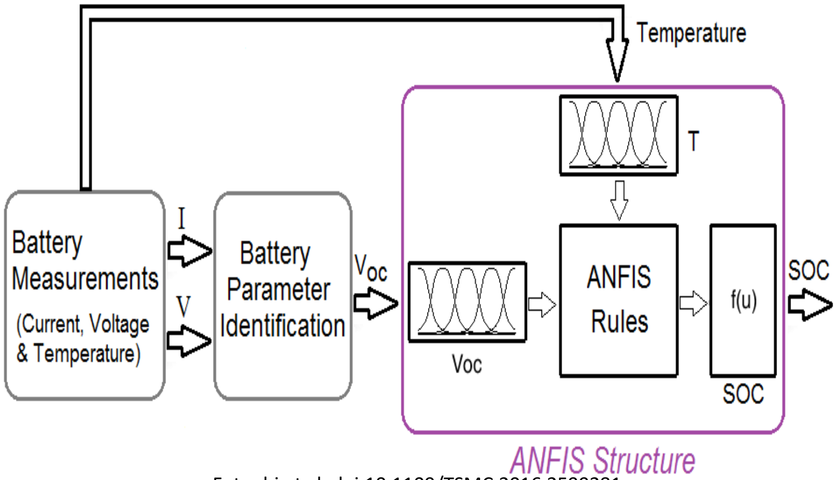
- Assumes uncertain system dynamics.
- Fast system identification methods, e.g. Prediction Error Minimization, grey-box model identification.
- Optimization-based state estimation, e.g. Kalman filter derivatives.



[Source: Propp 2014]

Technique 2: From Computer Science

- Trained expert systems.
- Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combined with a current integral model.



Fotouhi et al, doi:10.1109/TSMC.2016.2599281

Both Techniques use **Equivalent Circuit Network (ECN) Models**.

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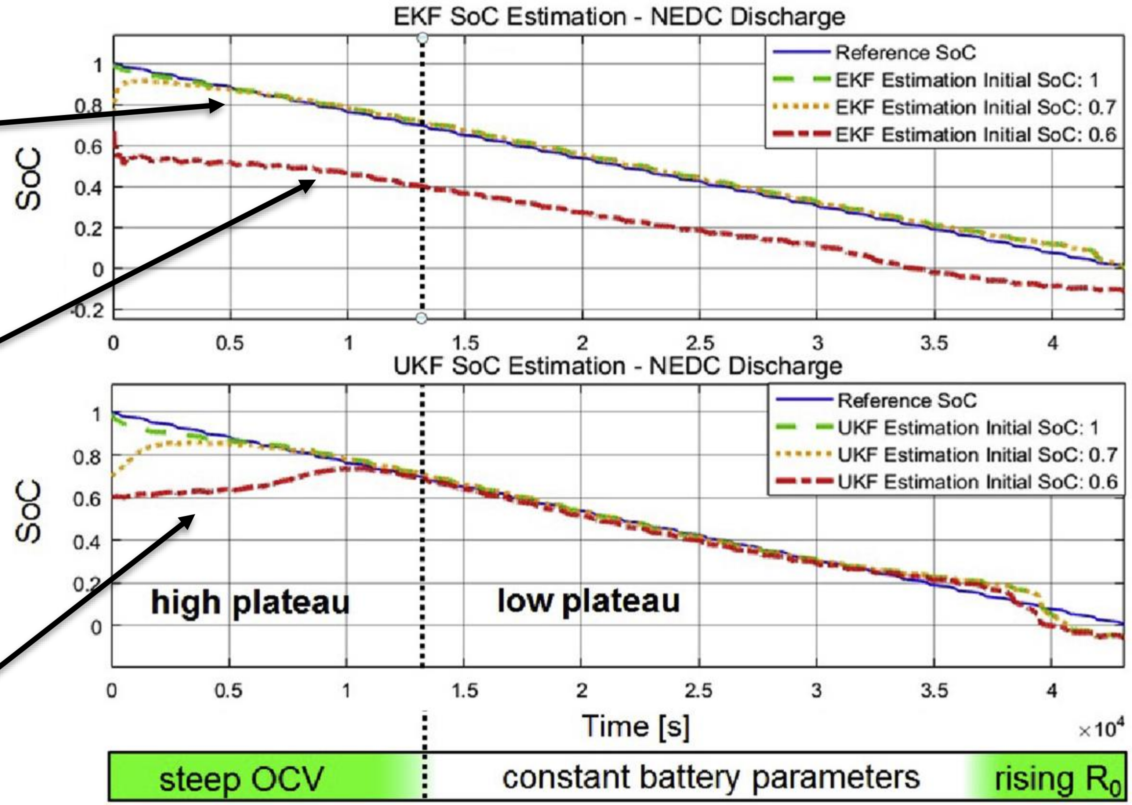
Technique 1: Extended and Unscented Kalman Filters

Extended Kalman Filter (EKF) works well provided initial state is reasonably well-known.

Not so good if there is a significant initialization error.

Unscented Kalman Filter (UKF) is slightly less good in best-case scenarios, but converges better when initial state is unknown.



Propp et al (2016), doi:10.1016/j.jpowsour.2016.12.087

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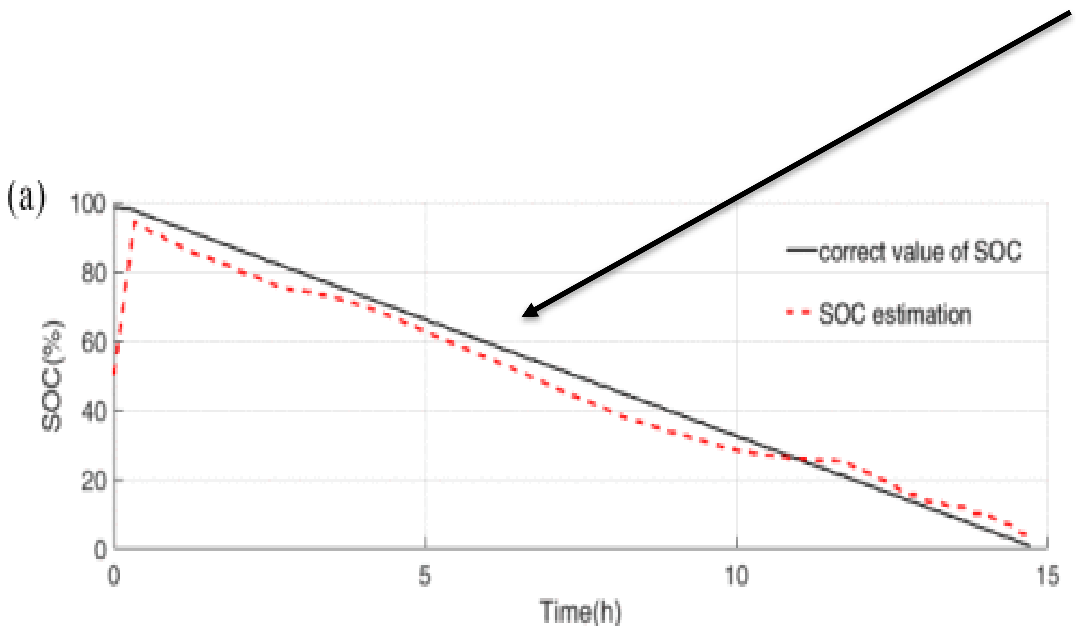
Technique 2: ANFIS/Current Integral Hybrid



ANFIS together with current integral gives mean error ~4% with UDDS automotive cycle.

It can converge well when initial state is unknown (see full paper for details).

Fotouhi et al,
doi:10.1109/TPEL.2017.2740223

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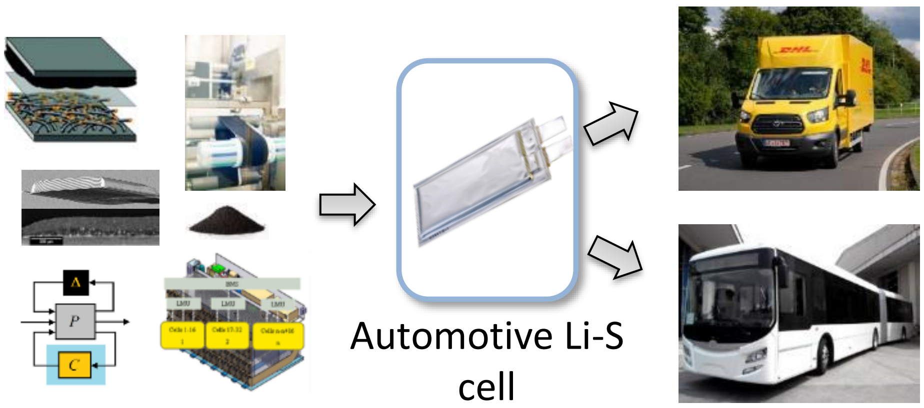
LiS:FAB

Lithium-Sulfur: Future Automotive Battery

- £7.6m collaborative project (us: £840k).
- Developing a next-generation 400 Wh/kg+ lithium-sulfur cell for large electric vehicles.
- To transition to production, module development techniques are a major work package.
- Cranfield's battery management algorithms allow easy deployment in applications.

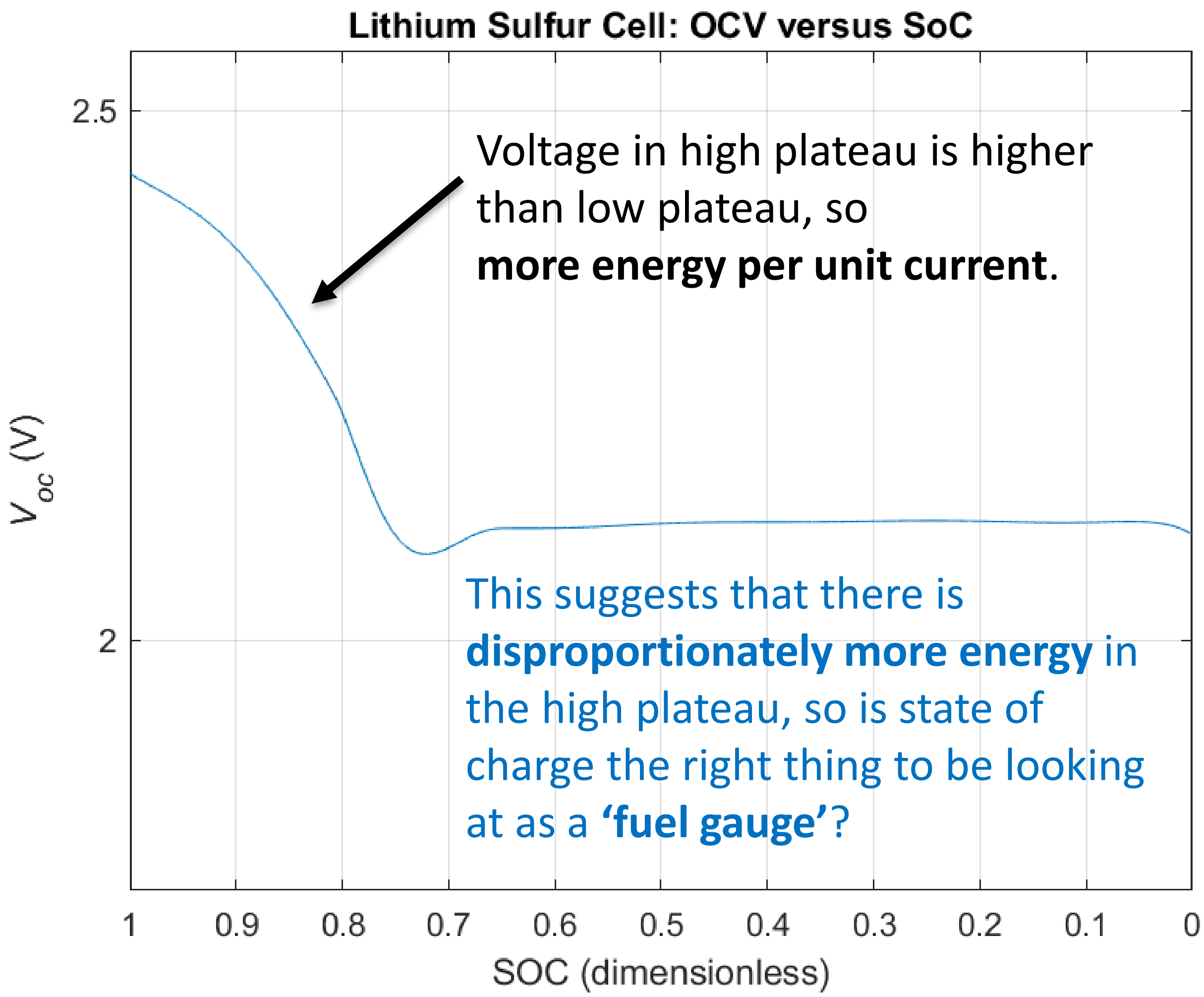


Cranfield's work on this project is funded by

Innovate UK

under grant no. TS/R013780/1

Why look at state of energy?



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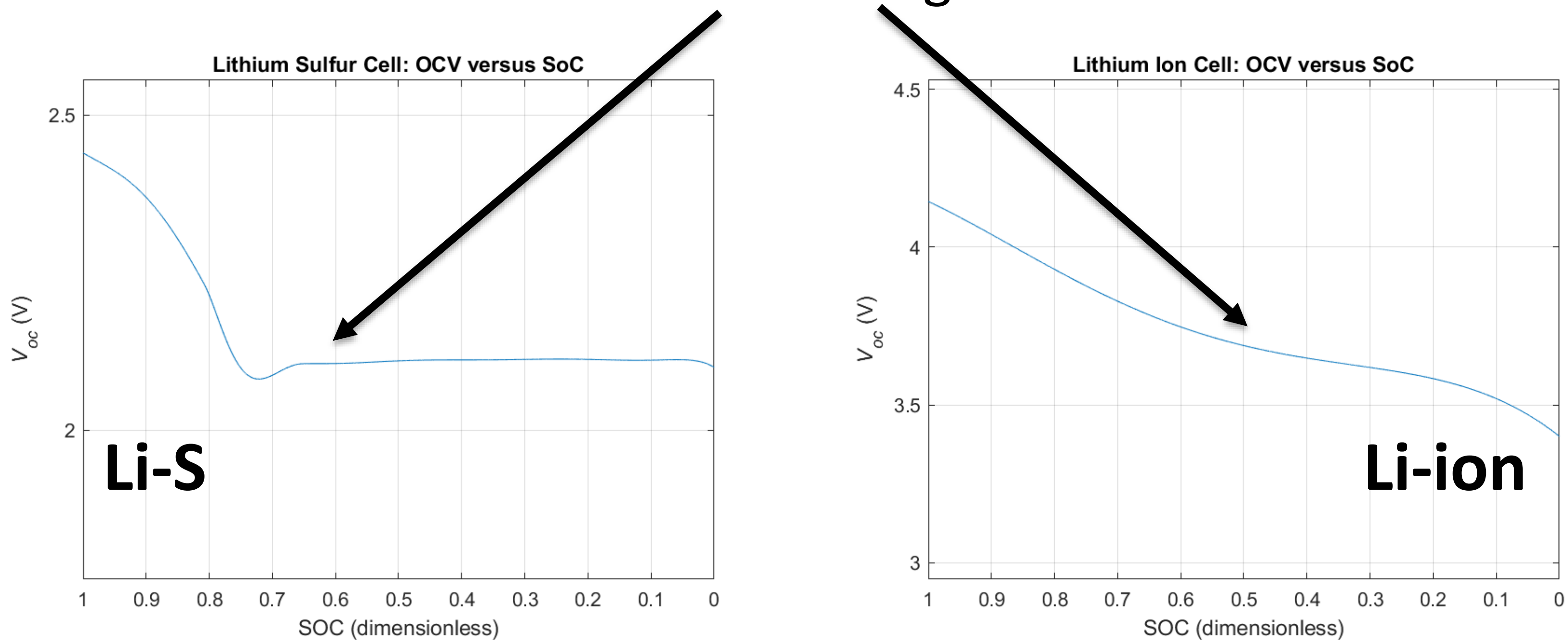
Why is it different from Li-ion?

The character of Li-S is **more skewed** than Li-ion at the higher SoC end



Does this mean it has **greater significance** in Li-S?

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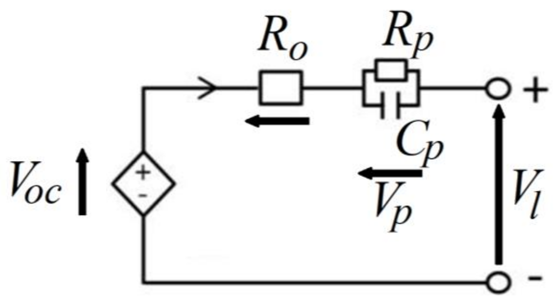
What is ‘state of energy’? Definition 1: Energy in Battery

$$\widehat{W}_{oc} = \frac{\bar{E}_{oc} - \int_0^t V_{oc}\, I_\ell\; d\tau}{\bar{E}_{oc}}$$

where

- $\widehat{W}_{oc}$ is state of energy
- $\bar{E}_{oc}$ is the energy in the battery when fully charged
- V_{oc} is open-circuit voltage
- I_ℓ is load current



$$\bar{E}_{oc} = \int_{\text{discharge}} V_{oc}\, I_\ell\; dt = \int_{\text{discharge}} V_{oc}\; dQ_\ell$$

This definition does not take into account any losses in the battery, but it is very easy to work with since the open-circuit voltage is independent of current.

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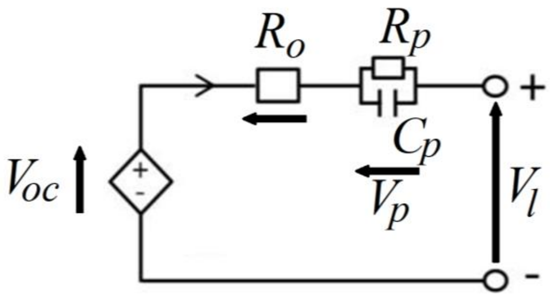
What is 'state of energy'?
Definition 2: Capacity to Do Work

$$\widehat{W}_\ell = \frac{\bar{E}_\ell - \int_0^t V_\ell\, I_\ell\ d\tau}{\bar{E}_\ell}$$

where

- $\widehat{W}_\ell$ is state of energy
- $\bar{E}_\ell$ is the energy in the battery when fully charged
- V_ℓ is load voltage
- I_ℓ is load current

$$\bar{E}_\ell = \int_{\text{discharge}} V_\ell\, I_\ell\ dt \qquad \text{(no change of variables)}$$



This is potentially more useful, but the challenge here is that the load voltage depends on the current so we can only calculate it after the event – unless the current is known in advance.

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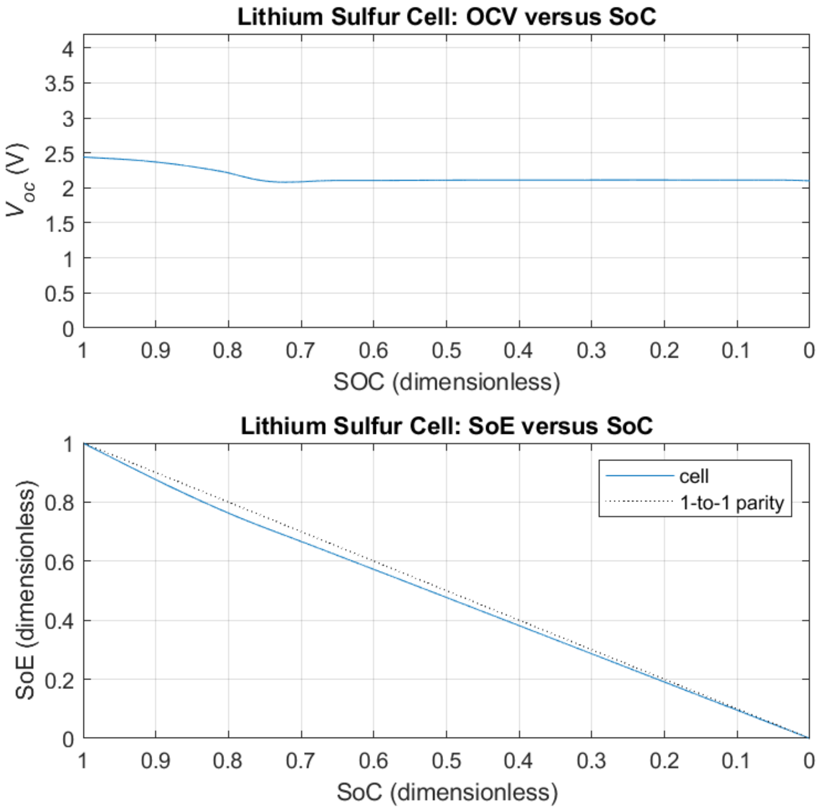
How it Works Out:
In Theory (1)

Explored with a lithium-sulfur model that has already appeared in the literature by **Propp et al:**

[10.1016/j.jpowsour.2016.07.090](https://doi.org/10.1016/j.jpowsour.2016.07.090)

The first definition of state of energy was applied.

- For low current loads, the two definitions converge.



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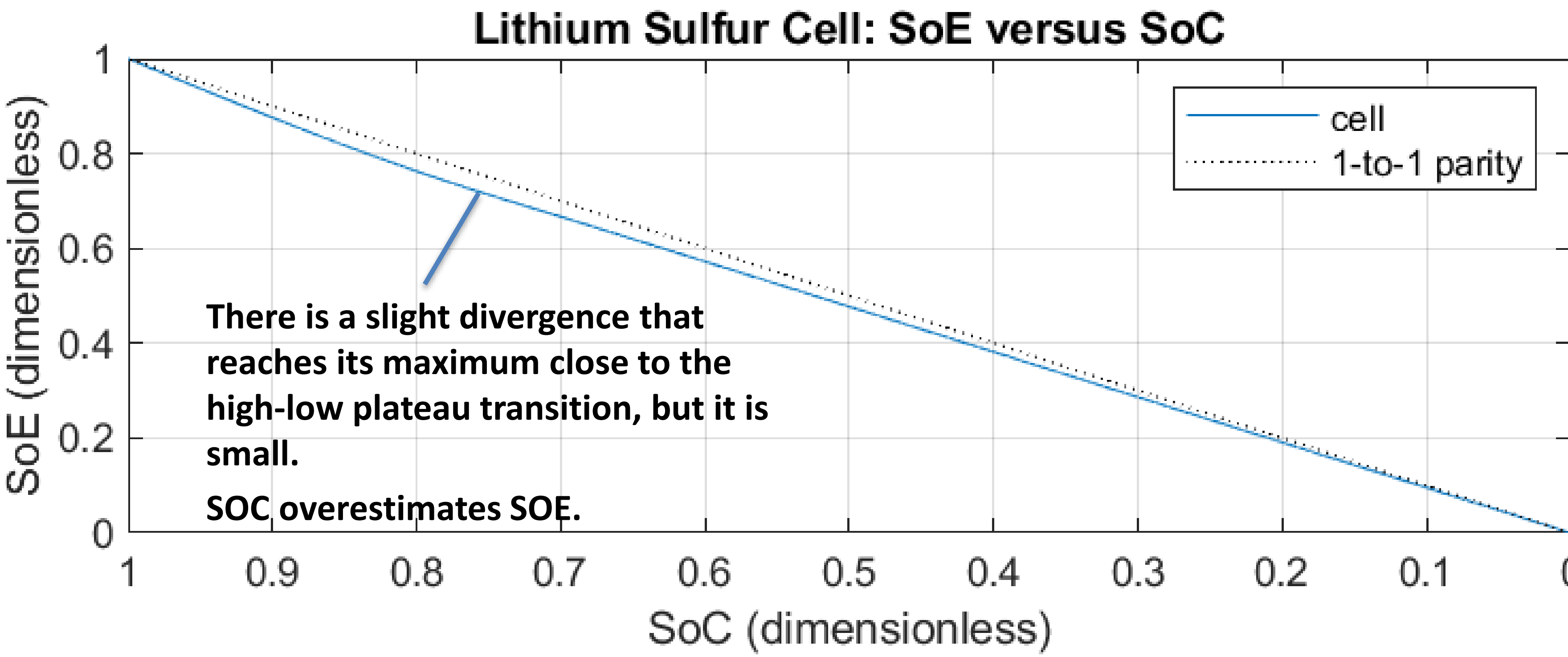
How it Works Out:
In Theory (2)



There is a slight divergence that reaches its maximum close to the high-low plateau transition, but it is small.

SOC overestimates SOE.

Overall SOC and SOE are very close in value for this theoretical test.

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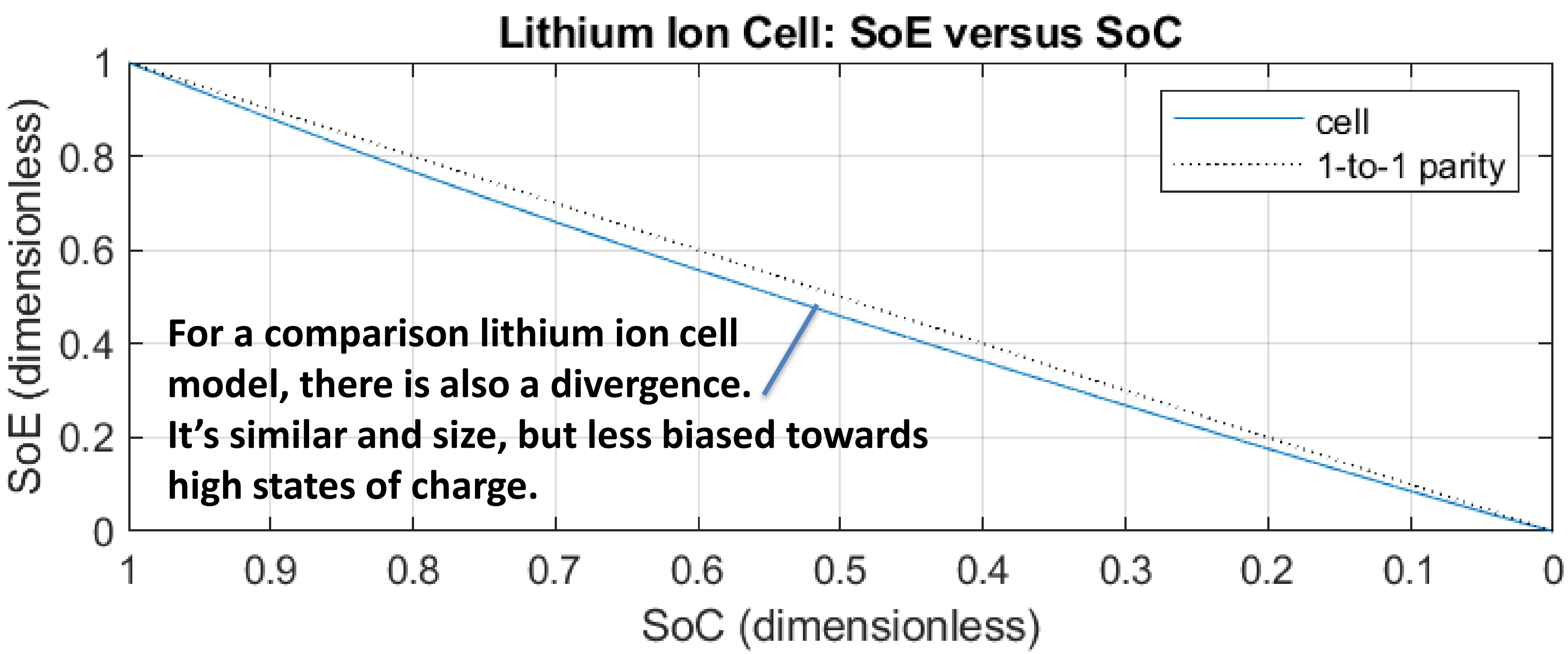
How it Works Out: In Theory (3) – Comparison with Li-ion



For a comparison lithium ion cell model, there is also a divergence. It's similar and size, but less biased towards high states of charge.

The comparison model was based on Antalaoe et all, DOI: 10.1109/TVT.2012.2212474

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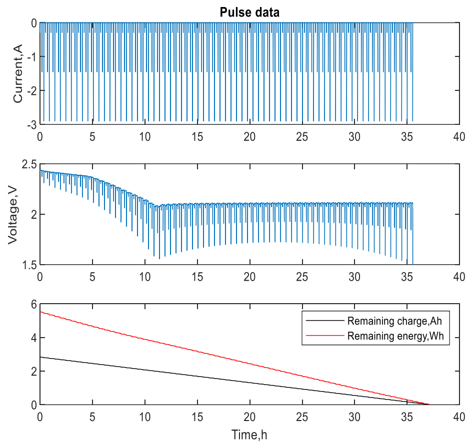
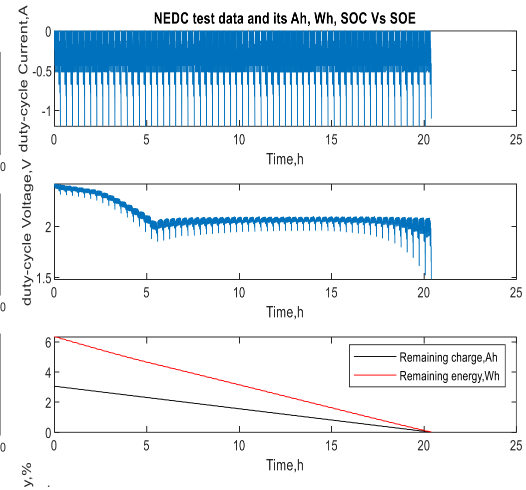
How It Works Out: In Practice (1)

Two data sets from a legacy project

- one is for pulse-discharged data
- other is for drive cycle data
- described at [10.1016/j.jpowsour.2016.07.090](https://doi.org/10.1016/j.jpowsour.2016.07.090)





These represented a moderately low output (approx. 1C max, often less).

State of energy was calculated from

$$\widehat{W}_\ell = \frac{\bar{E}_\ell - \int_0^t V_\ell \, I_\ell \; d\tau}{\bar{E}_\ell} \qquad \bar{E}_\ell = \int_{\text{discharge}} V_\ell \, I_\ell \; dt$$

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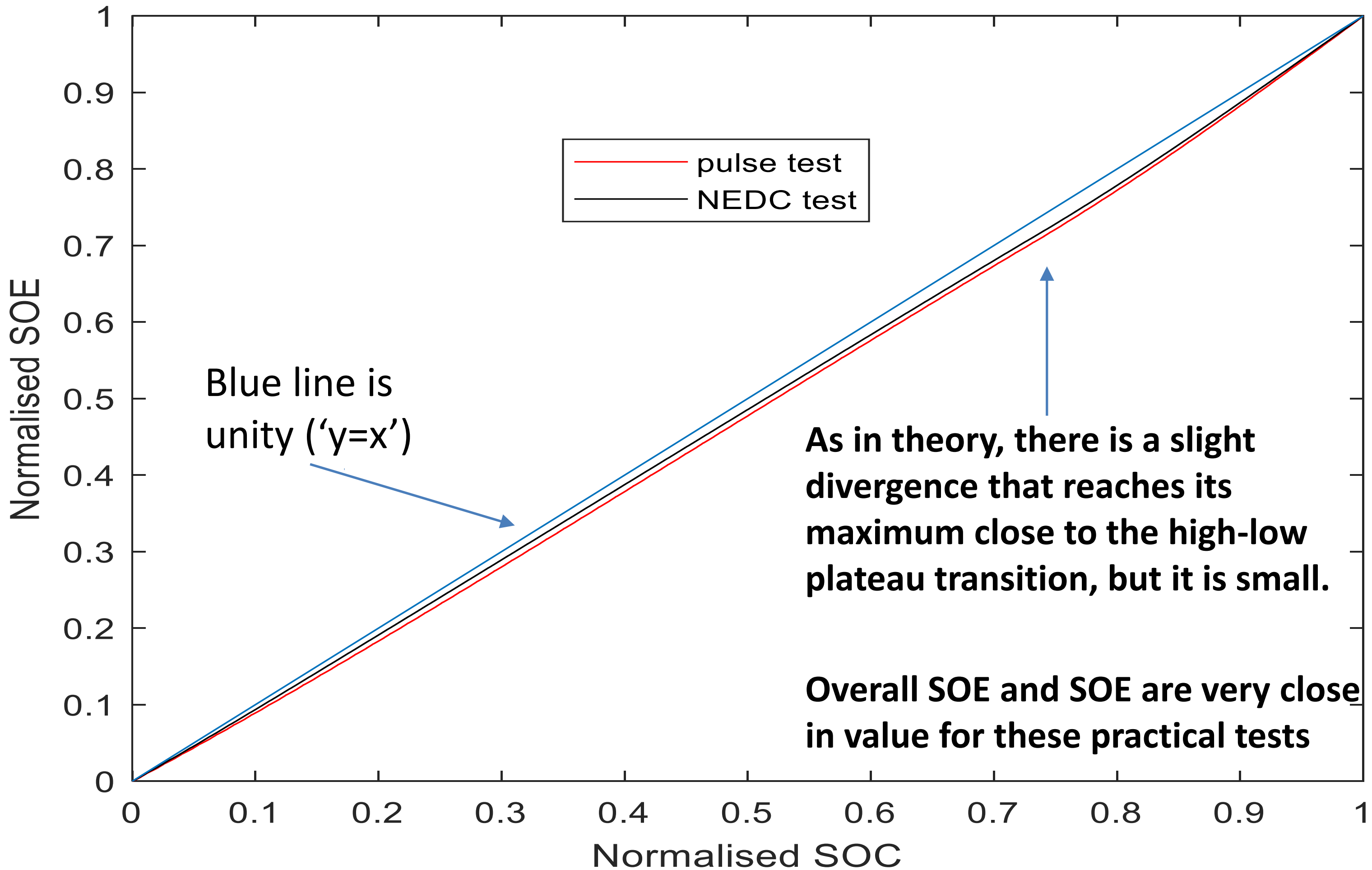
How It Works Out: In Practice (2)



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Key Findings and Discussion

Findings and Observations

- At the moderate current intensities considered, there is little difference between SOC and SOE.
- There characteristic shape is different to the lithium ion battery considered, though probably not ‘worse’.
- An awareness of the SOC/SOE characteristic might be useful to designers.
- There is probably little benefit in reformulating our state observers in terms of SOE – having a useful mapping is enough.

Areas for Further Study

- The impact of very high current intensities has not been considered. This would be interesting to see.
- At the moment, our work has considered a ‘battery as a cell’ and been limited to electrical considerations.
- It would be helpful to extend this to the ‘battery as a system’ (including temperature regulation).
- This needs good thermal models of cells.

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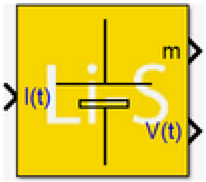
Conclusion / Acknowledgements

- Context - Cranfield's team and facilities
- State Estimation
  - Key Challenges
  - Techniques
- State of Energy in Lithium-Sulfur
  - Motivation
  - Definitions
  - Theory and Practice
  - Future Directions
- Conclusion / Acknowledgements

Funding: Innovate UK

This work was partially funded by Innovate UK under grant no. TS/R013780/1



our lithium-sulfur cell model for Simulink is ***free*** *from the* *MATLAB File Exchange*

Key references are given on the slides.
Background material has been presented before at the following conferences and events:

Lithium-Sulfur Batteries, Dresden, November 2018
Li-SM3, Chicago, April 2018
Li-SM3, London, February 2016 and April 2017
EMN Meeting on Batteries, Orlando, February 2016
Hybrid and Electric Industrial Vehicle Technology, Cologne, November 2016
Talk to the Control Group, University of Oxford, February 2017

This presentation's co-authors

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