Nissan Leaf

AI-Driven and Model-Based Battery Manufacturing Process Optimisation & Control

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Nov 2024

THE FARADAY INSTITUTION
ELECTRODE MANUFACTURING

NEXTRODE

Warwick Manufacturing Group, University of Warwick






Intelligent Vehicles

Materials

Digital Technologies

Social Transformations

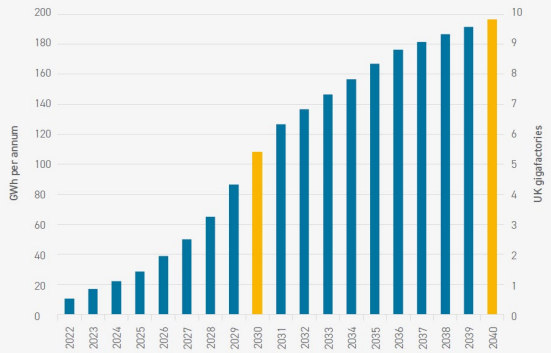
Energy

- Battery Manufacturing Scale up
- Battery Systems Engineering
- Cell, module and pack Engineering
- Characterisation, Modelling, Control
- Electrochemical materials
- Power Electronics, Machines
- Vehicle Propulsion
- Reuse and Recycle

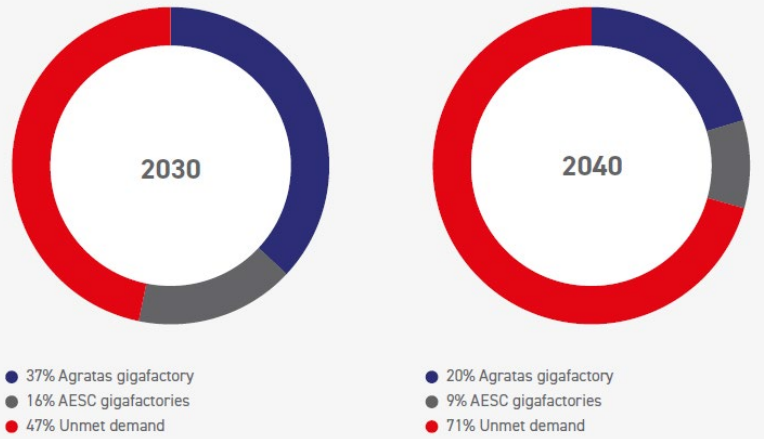
WMG THE UNIVERSITY OF WARWICK

- Battery Manufacturing Process Optimisation Goals
- Ramp up challenge
- Models for process optimisation and control
- Case Studies
- Lessons Learnt

UK ELECTRIC VEHICLE AND BATTERY PRODUCTION POTENTIAL TO 2040



By 2040, around 200 GWh of supply will be needed in the UK to satisfy the depend for batteries for private cars, commercial vehicles, HGVs, buses, micromobility and grid storage



By 2040, around 200 GWh of supply will be needed in the UK to satisfy the demand for batteries. 71% of this demand remains unfulfilled, highlighting the need to attract further significant investment

UK, 2040

10 gigafactories required in the UK by 2040 (assuming each plant has a capacity of 20 GWh pa)

200 GWh pa demand for batteries in the UK in 2040

71% of the demand for UK gigafactories to 2040 has yet to be met by announced plans

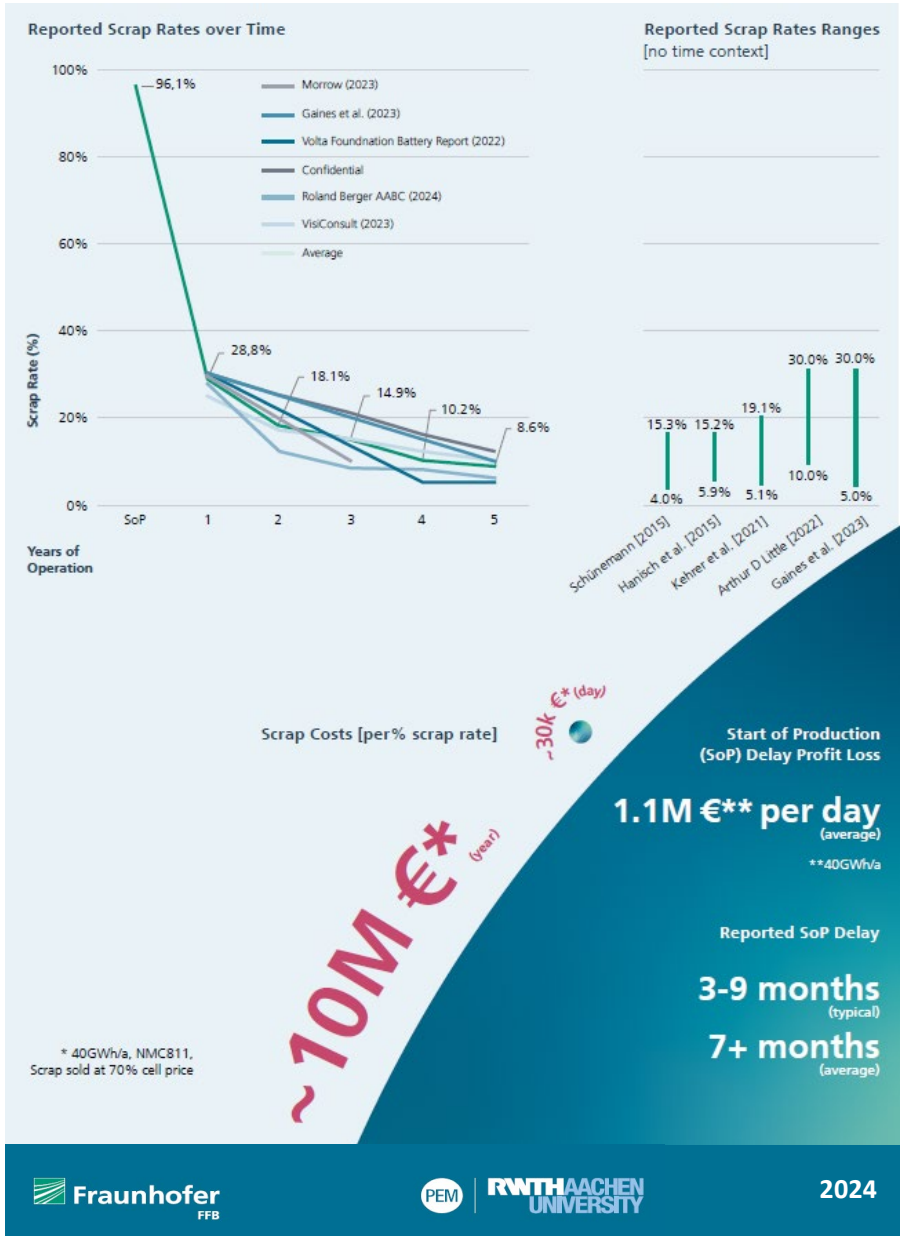
82% of the total UK battery demand to 2040 will be from EVs and light commercial vehicles

The Faraday Institution
UK Gigafactory Outlook (September 2024)

THE FARADAY INSTITUTION

UK electric vehicle and battery production potential to 2040

RAMP UP CHALLENGE



Manufacturer	Location	Status
ABEE	Romania	Cancelled
ABF (American Battery Factory)	United States	Postponed
ACC	Germany	Paused
ACC	Italy	Paused
AMTE Power	United Kingdom	Cancelled
Blackstone	Germany	Cancelled
Britishvolt	United Kingdom	Cancelled
Farasis Energy	Germany	Cancelled
Ford	United States	Scaled down (-40%)
Freyr Battery	Norway	Delayed (6 months)
Innolith	Switzerland	Paused
Inobat	Slovakia	Production capacity postponed (1 year)
Italvolt	Italy	Cancelled
Koc Holding/Ford/LGES	Turkey	Cancelled
Kreisel	United States	Postponed
Microvast	United States	Paused
Northvolt	Sweden (Borlange)	Cancelled
Northvolt	Sweden (Skelleftea)	Delayed
Northvolt	Germany	Paused
Our Next Energy (ONE)	United States	Postponed
PowerCo	Europe	Cancelled
Stellantis/LG	Canada	Postponed
SVOLT	Germany	Cancelled

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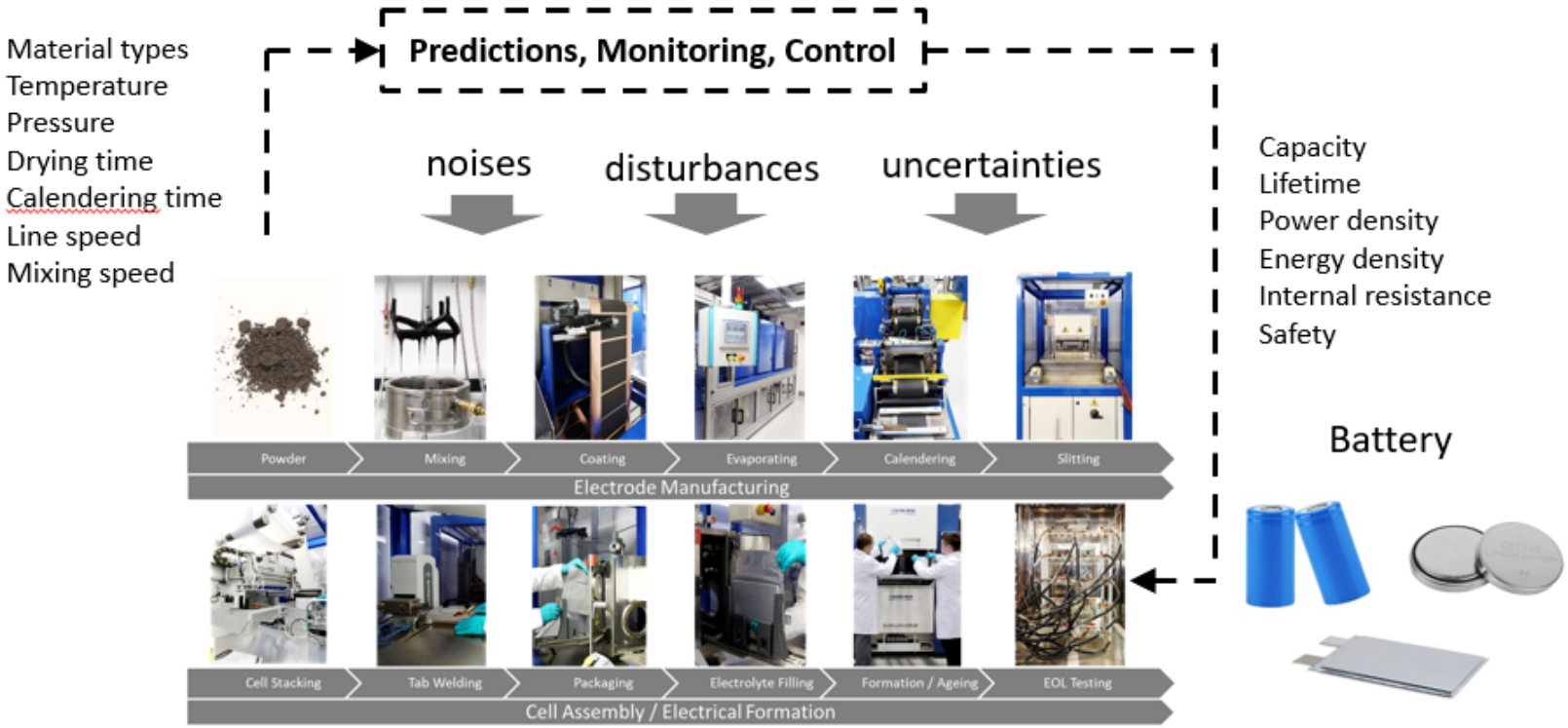
ELECTRODE MANUFACTURING



WMG Pilot Line of Cell Manufacturing

Trial and Error Based Approach

- Material selection
- Formulation Design
- Equipment setting
- Instrumentation set up
- Quality control

Model-Based Approach

- Formulation Optimisation
- Process Optimisation
- Product Improvement
- Predictive Maintenance

MANUFACTURING OVERVIEW

Electrodes and half Cells

1st DoE

Anode and Cathode

32 experiments

Focus on Structural features
Thickness, Porosity, Mass Loading
Capacity
Correlation analysis
Importance and ranking analysis

Screening Coating and Drying

Anode and Cathode

32 experiments

Structural, electrochemical features
Thickness, Porosity, Mass Loading
Capacity, Resistance
Correlation analysis
Interpretable ML models

2nd DoE

Electrodes and half Cells

Surface Response Coating and Drying

Manufacturing process improvements

Rev

3rd DoE

Coin and Pouch Cells

Anode and Cathode

14 experiments

Focus on electrochemical features
Generalisation analysis
Capacity, Resistance, Lifetime
N:P, anode and Cathode thickness
Anode and Cathode mass loading

Full Cell Coating and Drying

Anode and Cathode

36 experiments

Focus on structural and electrochemical features
Correlation analysis
Machine Learning models
Temperature, calendering gap, porosity
Capacity, Resistance, Lifetime

4th DoE

Electrodes and half Cells

Calendering

Slurry Mix, Electrodes and half cells

5th DoE

Cathode

22 experiments

Slurry and electrochemical features
Machine Learning models
Multi criteria optimisations
Viscosity, Density, surface Tension, Thickness, Porosity, Mass Loading
Capacity, Resistance, Lifetime

LFP Formulation

Cathode

90 experiments

Slurry and electrochemical features
Machine Learning models
Multi criteria optimisations
Capacity, Resistance, Lifetime
EIS

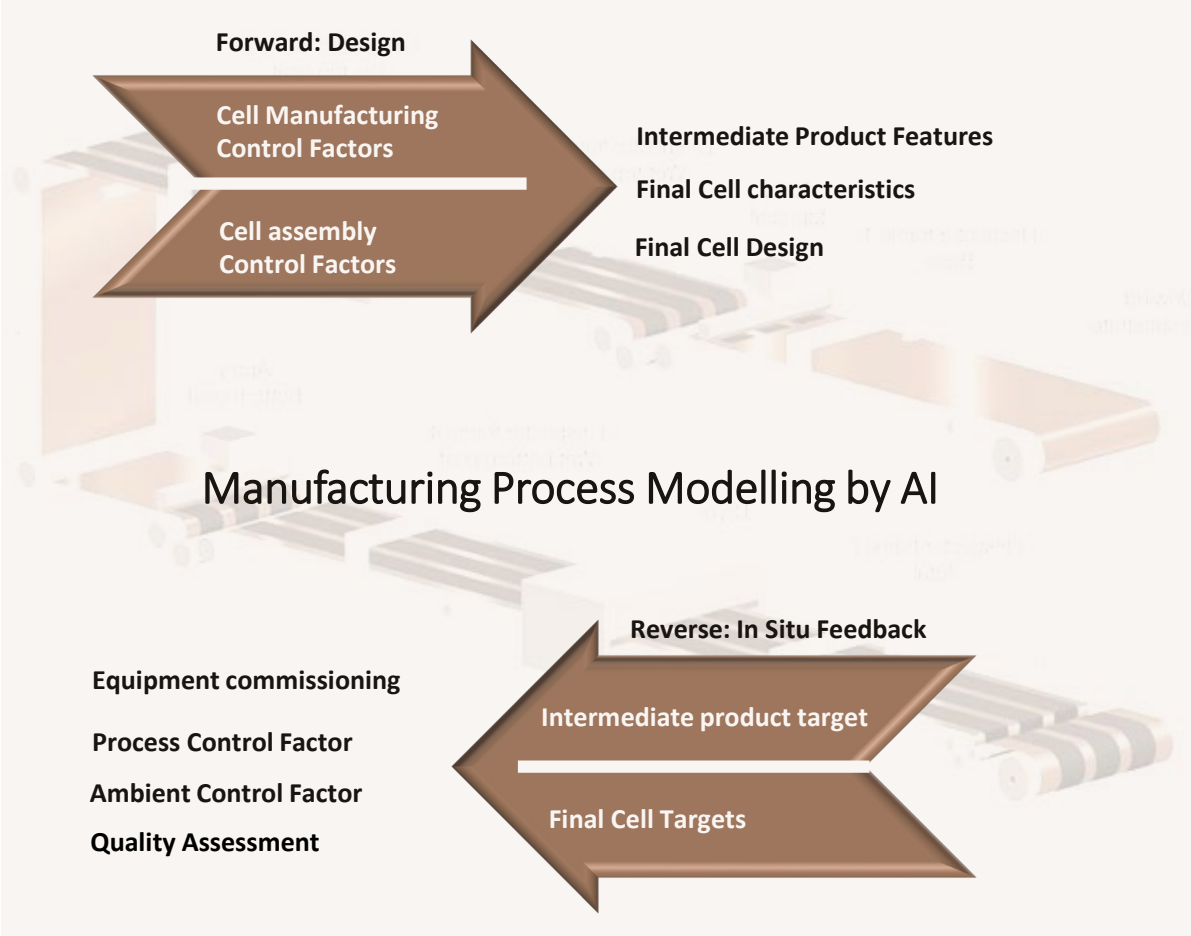
6th DoE

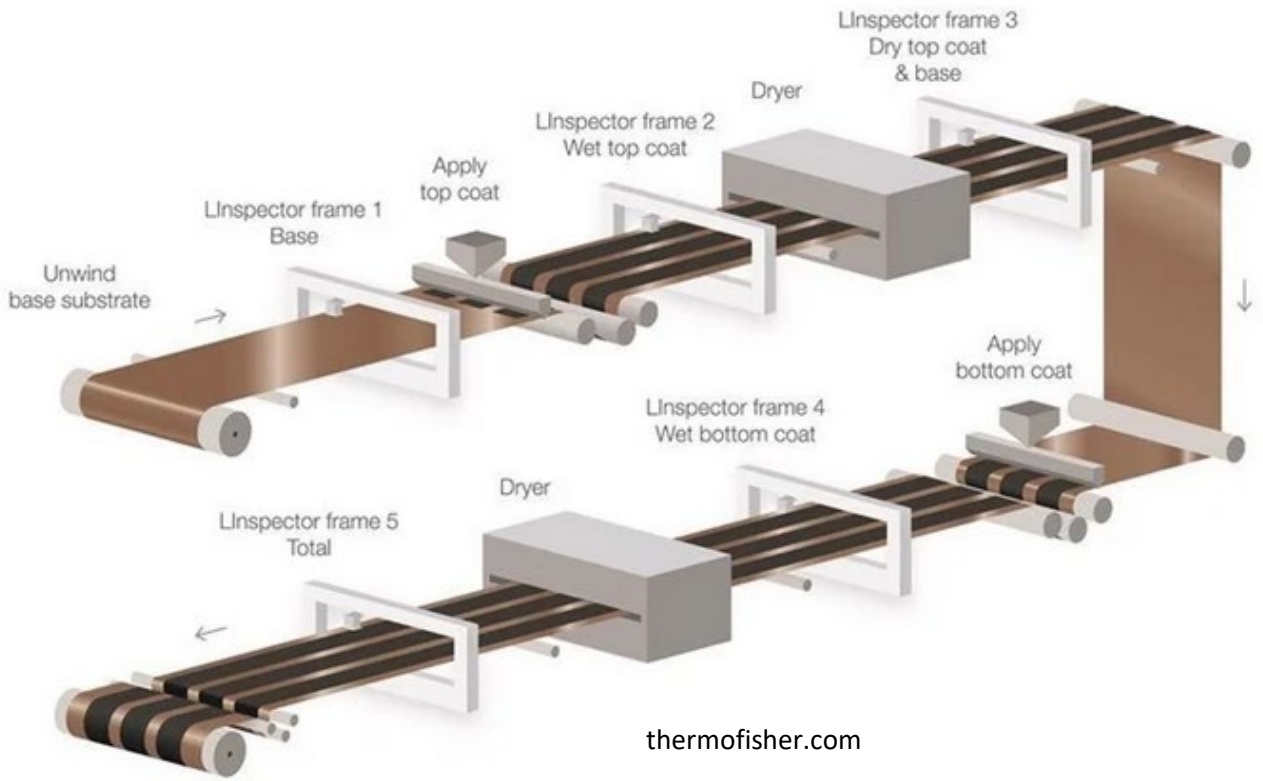
Slurry Mix, Electrodes and half cells

Mixing

MODEL-BASED ELECTRODE MANUFACTURING

Comprehensive Digital Twin





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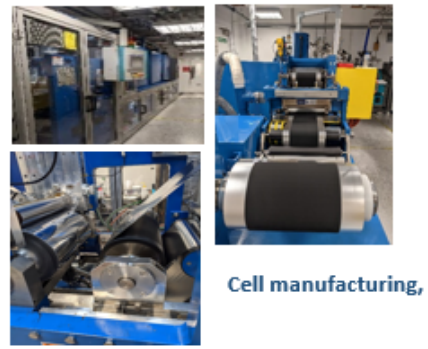
Reduce waste
Commissioning time and effort
Changning the target and requirements

STEPS TO MODEL-ASSISTED SHORTCUT

Business understanding

Battery Manufacturing Chain

Electrode Manufacturing | Cell Assembly | Final Cell



Cell manufacturing, and Experiments

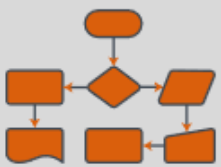
Design of Experiments

Data handling

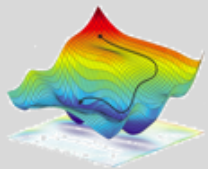
Data Collection/Storage/Cleaning

Optimisation

Optimisation and Control



Recommendations

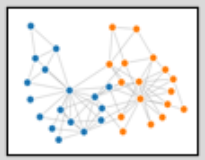


Multi Objective Optimisation

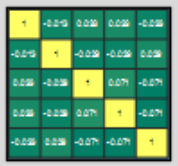
Expert Domain Knowledge

Assessment

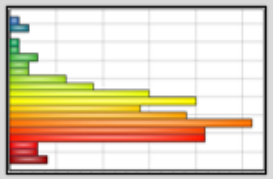
Explanation/Interpretation



Interactions

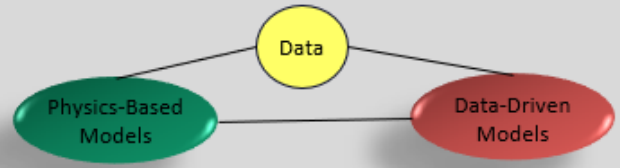


Correlations



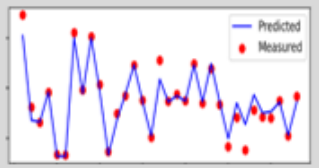
Multi C Assessment

Physics – Aware Machine Learning Models



Cyber World/AI Model Development

Classification

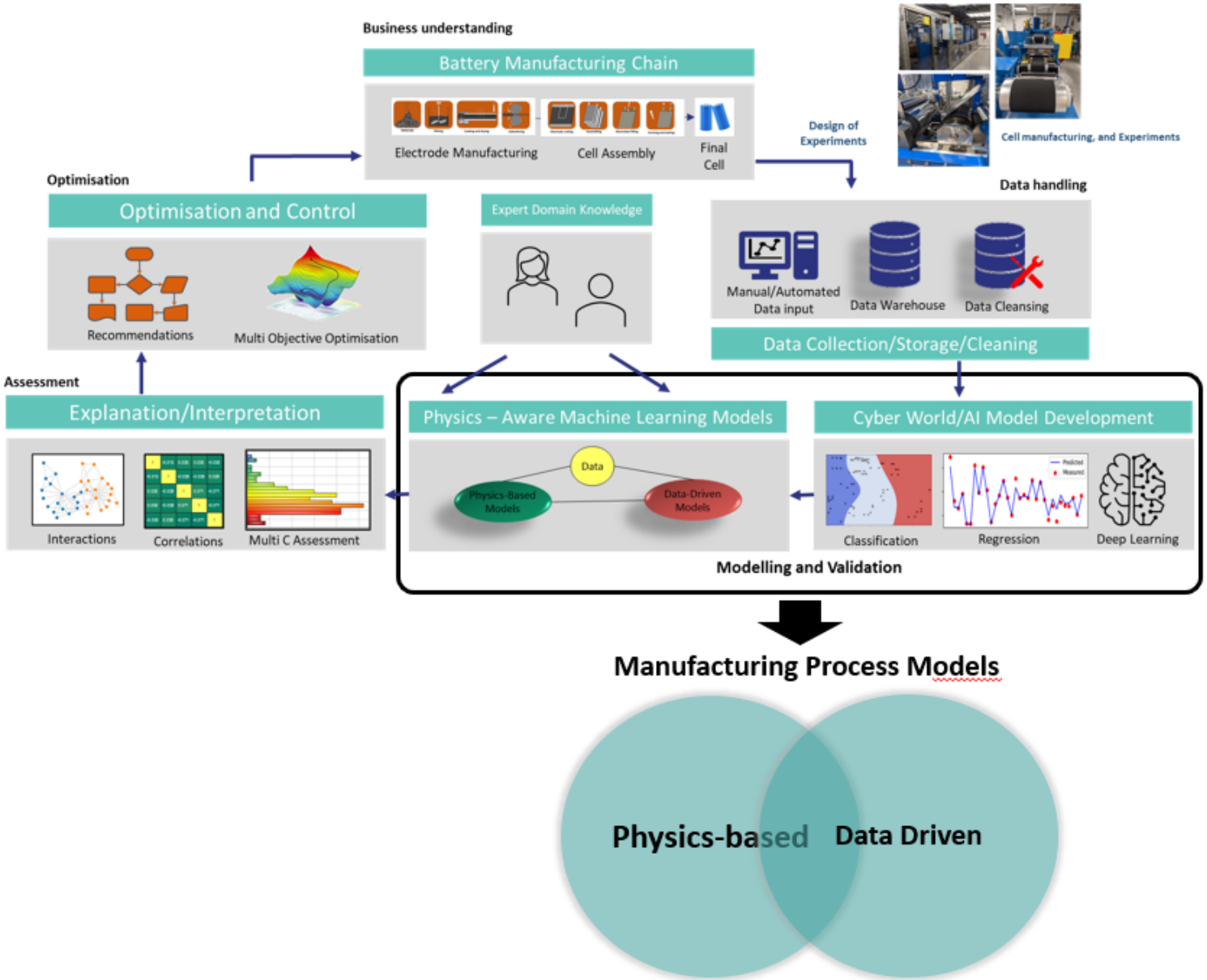


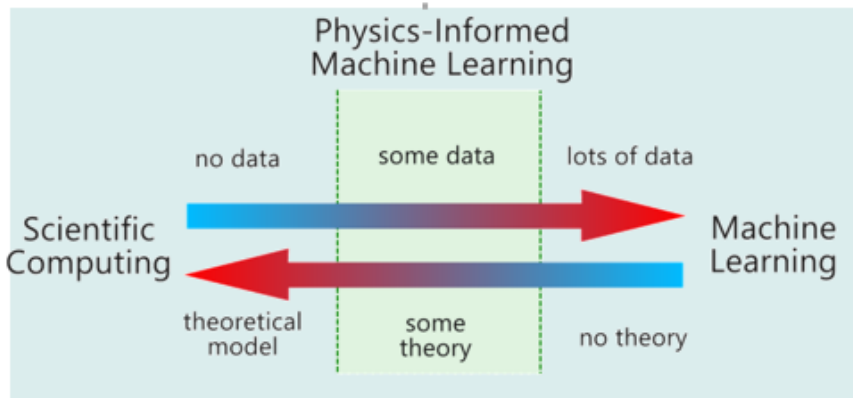
Regression

Deep Learning

Modelling and Validation

TRUSTWORTHY AI-ASSISTED DEVELOPMENT IN BATTERY MANUFACTURING

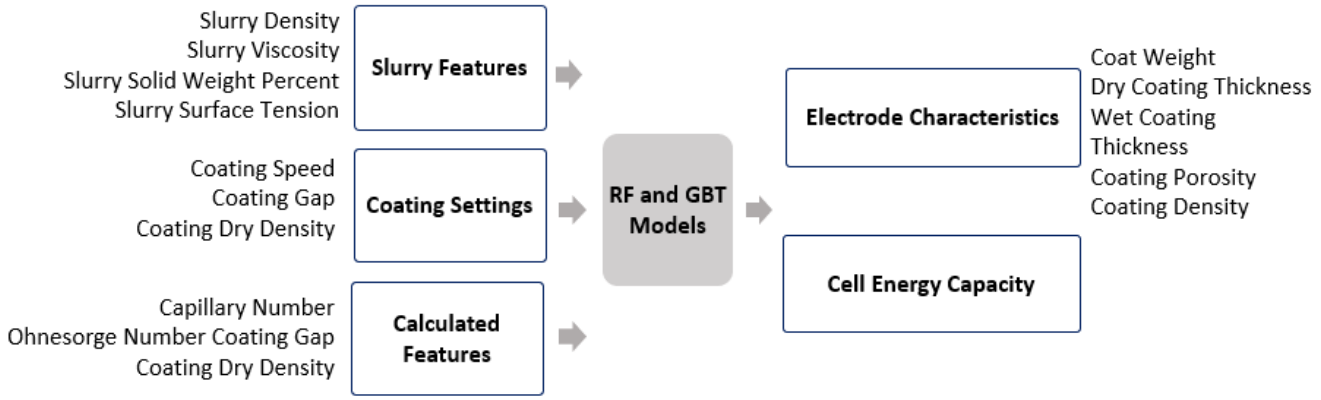




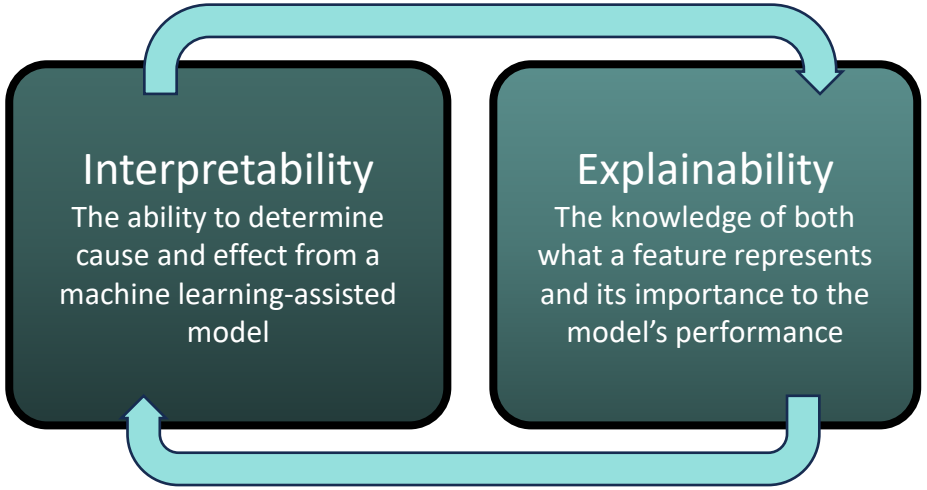
Incorporating Known physics in the form of the PDEs into the cost function of AI models

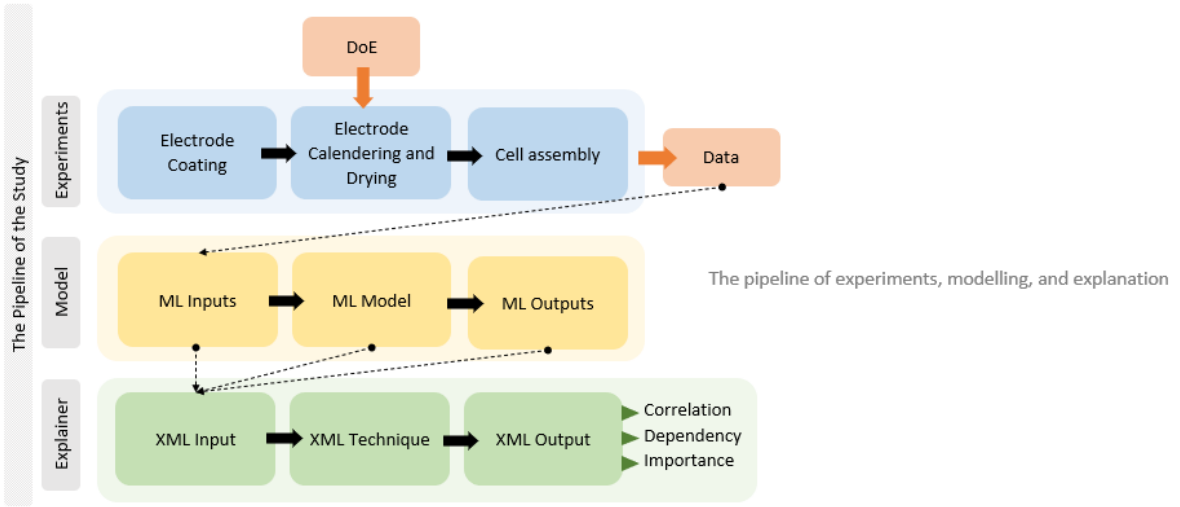
Physically consistent surrogate AI models based on Physics-based models

EXPLAINABLE AND INTERPRETABLE HYBRID MODELS



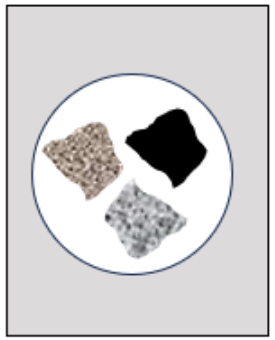
- **Interpretability in machine learning focuses on making the model itself more interpretable, simpler or more transparent model architectures**
- **Explainable machine learning focuses on providing explanations for the predictions of a machine learning model, regardless of the underlying architecture.**





The pipeline of experiments, modelling, and explanation

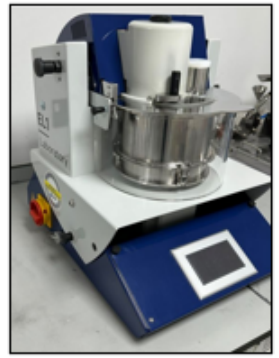
CASE STUDIES



Formulation

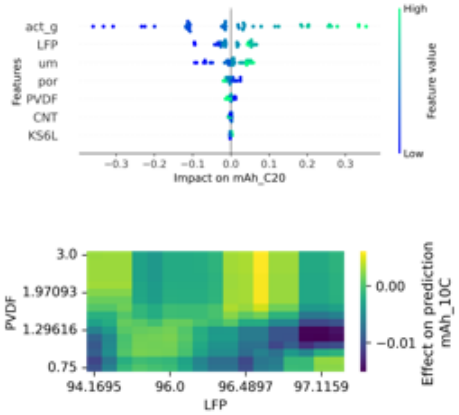
Coating

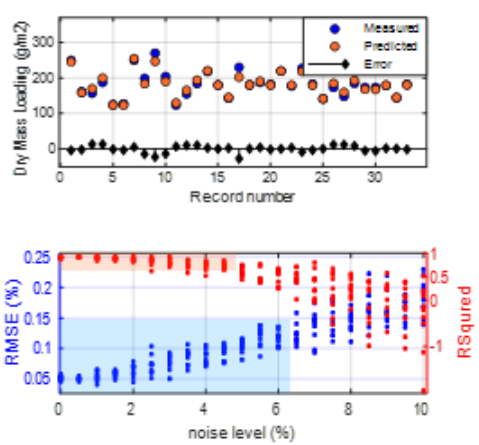
Calendering

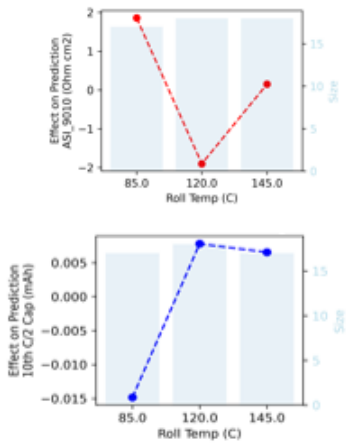


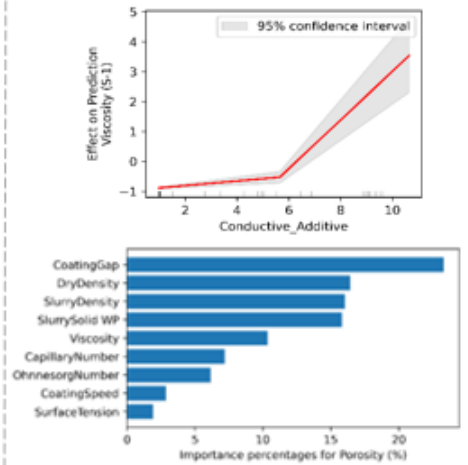
Mixing

Tests

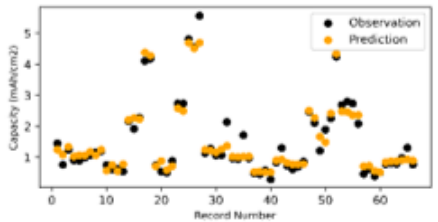








Capacity at C-Rates
ASI at SoCs%
Cycling Performance
Electrochemical Impedance Spectroscopy



Electrodes Structural features mask the formulations, and a focused study is encouraged

Conductivity and adhesion of the slurry are not much predictable only by the formulation

Multi-objective optimisation is successful in some cases

Electrodes Structural features are mainly linearly related to the coating setting

There are acceptable levels of noise and uncertainty tolerance by models

Roll Temperature has a sweet spot for both cell Capacity and ASI

Roll Pressure is a more significant factor than roll temperature

Coating factors mask mixing factors

Dimensionless number are contributing predictors

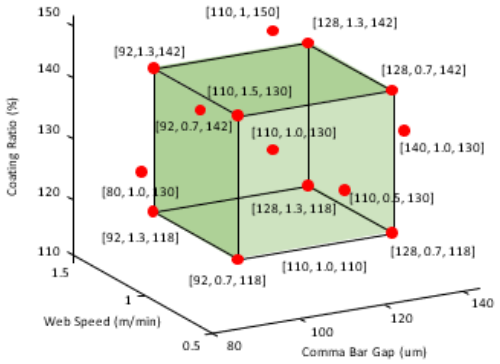
Slurry features and formulation have different dependencies

Capacity is highly predictable given process parameters

Predictability reduces after 50th cycle

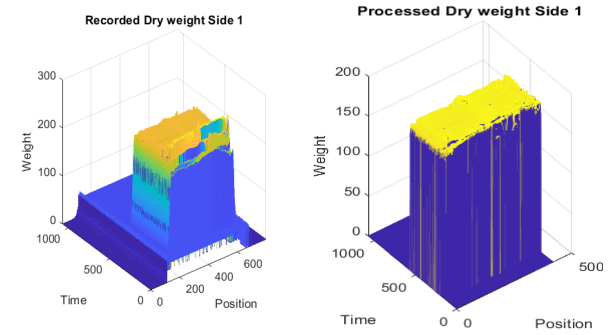
EIS performance is not predictable form with formulation

KEY LESSONS LEARNT



Data Quality

Systematic Data cleansing is prerequisite
Design of Experiments for a generating rich dataset with enough variability
Reverse prediction is only practical via a DoE
A minimum of three breakpoints is critical for nonlinearity capture

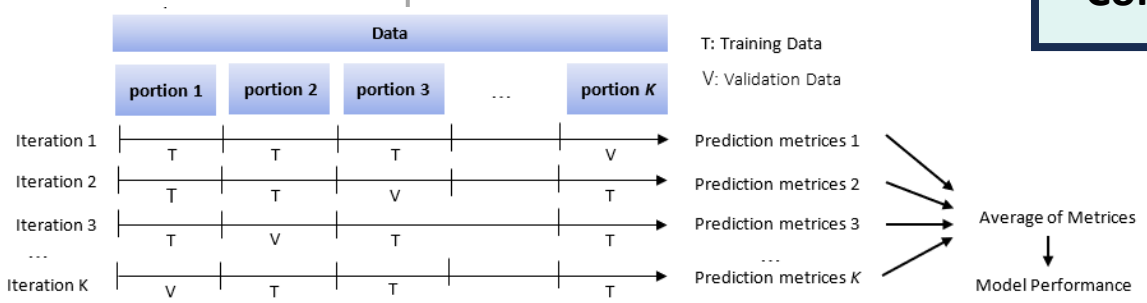


Data Size

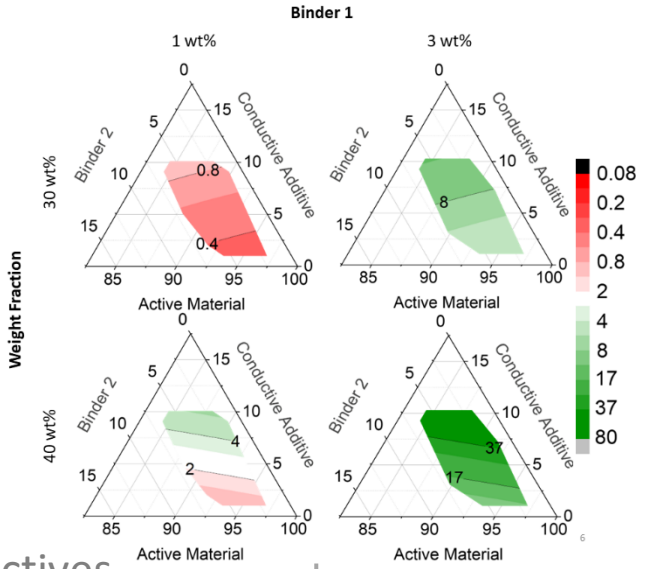
Dealing with small data is a key in manufacturing process modelling

Approaches involving below are preferred:

Cross validation,
Data augmentations
Data fusion is necessary in the process



Modelling Considerations



Objectives

Multi objective optimisation requires determining the importance weights in between the interested responses

The definition of the cost function is critical

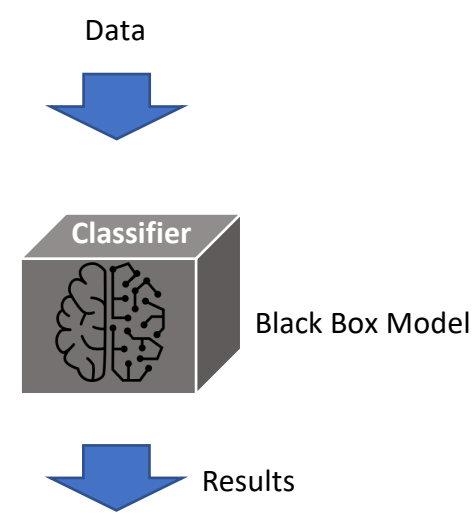
The consistency in between manufacturing processes for the modelling and the validation after optimisation is the key

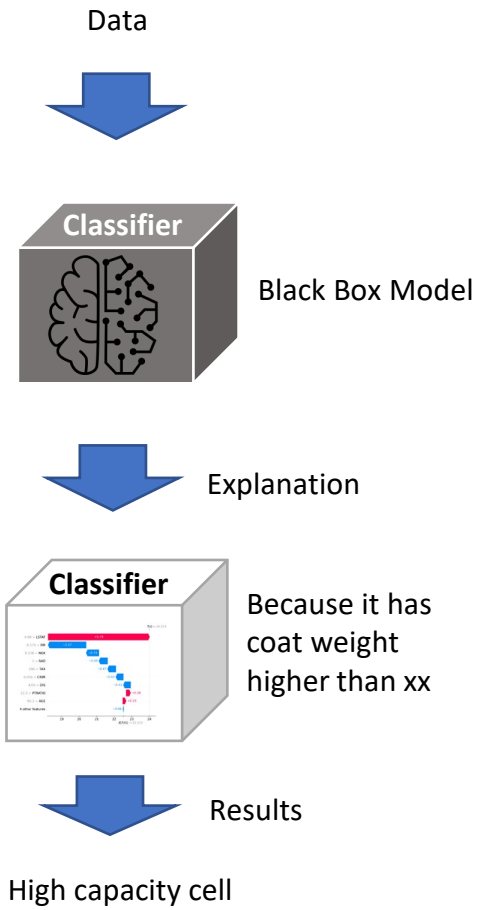
KEY LESSONS LEARNT

- Which Variables is masking others
- Which variable needs investment in instrumentation due to importance
- What is the most important experimental record
- What is the dependency and correlation strength
- What is the direction of impacts
- Why a particular prediction has been made

Challenges:

- Feedback to the model for performance improvement
- The cases that there are not any ground truth
- No benchmark data with enough explainability to prove the techniques trustability
- Explainability for time-series data or image data





IMPACTS

Quantifying the impact of factors	Prediction, interpretation, ensuring maximum accuracy in modelling
improve the production strategies	Identification of critical parameters affecting the quality to, lowering the development time and cost Reducing the number of experiments for cell manufacturing an
Development of corrective actions	Adaption of later processes or selective assembly of matching parts
high degree of quality transparency	Reasonable effort for design of experiments and modelling activities
model-based quality assessment	Where other quality checks are hardly applicable (e.g. after cell assembly)
Quality and environment	Increase the battery quality and reduce the environmental impacts caused per battery produced

PUBLICATIONS AND TALKS

Data

~210 mixes
~500 m of coating
~400 half coin cells
~100 full coin cells
~50 full pouch Cells

Tabular Data
Cycling data
Ageing Data
Images

- ✓ Data of Physical and Electrochemical Characteristics of Calendered NMC622 Electrodes and Lithium-ion Cells at Pilot-Plant Battery Manufacturing
- ✓ Experimental data of cathodes manufactured in a convective dryer at the pilot-plant scale, and charge and discharge capacities of half-coin lithium-ion cells
- ✓ LFP and Mixing Data in preparation

Publications

25 Journal papers
3 Review Papers
3 book chapters
7 conference papers/posters
5 Publications in preparation
11 Invited/Keynote talks

9th International Battery Technologies & BMS Conference
BATTERY TECHNOLOGIES For EV/HEV 2024

Thank you

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The Alan Turing Institute

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