A meta-analysis of the degradation rate of lithium-ion batteries

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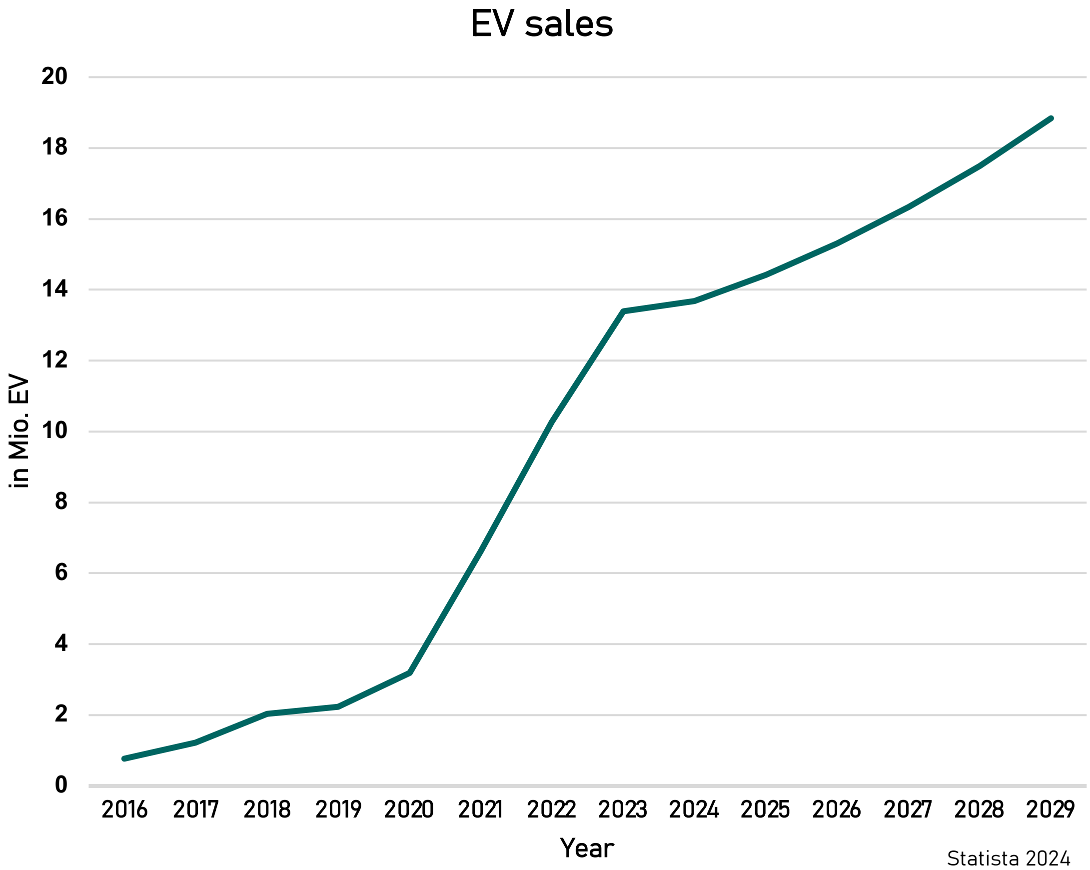
Work in progress paper

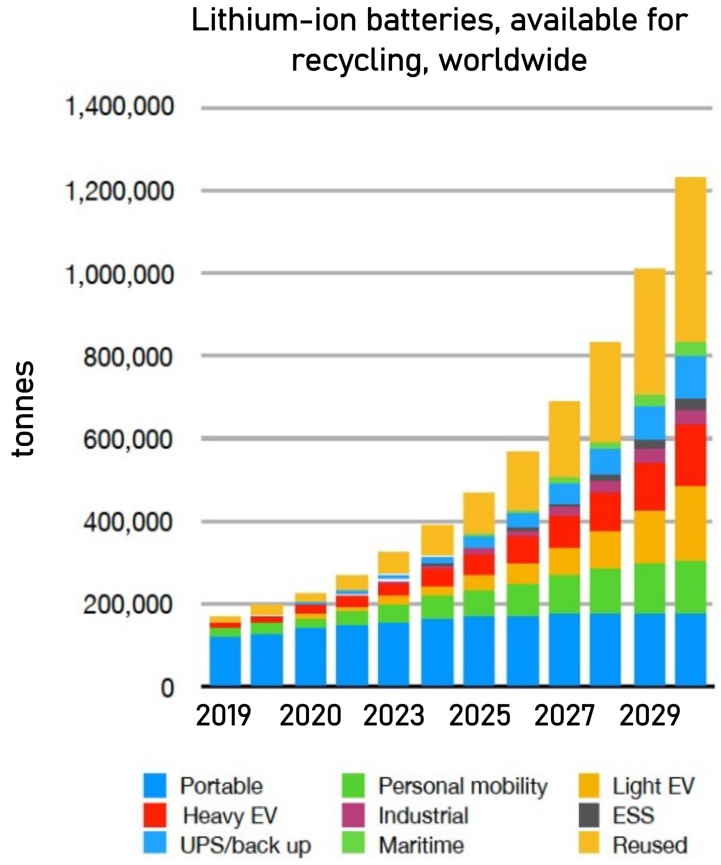
MAER-Net 2024, Augsburg, Germany

Introduction

High demand for lithium-ion batteries



Statista 2024

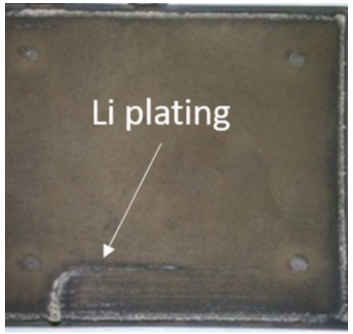


Jamasmie 2019

Degradation of Lithium-Ion Batteries

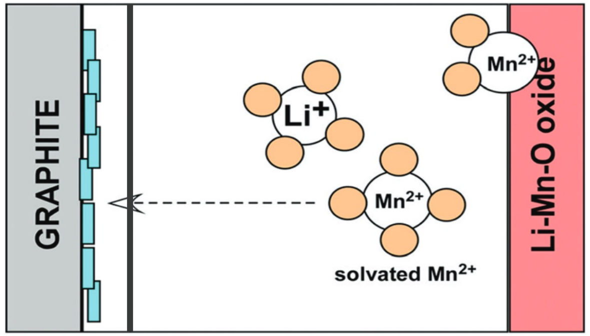
Most important factors influencing battery degradation

1 Li plating



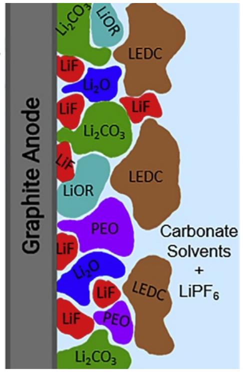
Edge et al. 2021

3 Active material dissolution

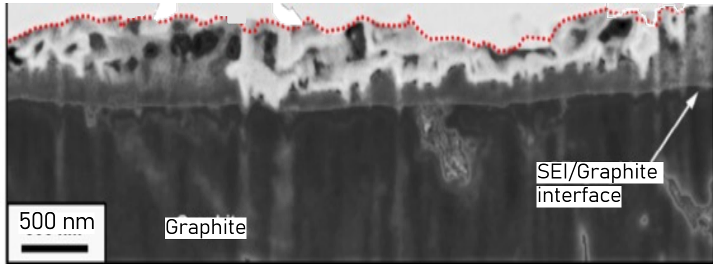


Zhan et al. 2018

2 Passive film formation

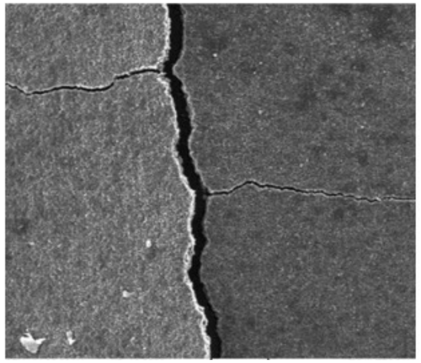


Heiskanen et al. 2019



Bhattacharya et al. 2020

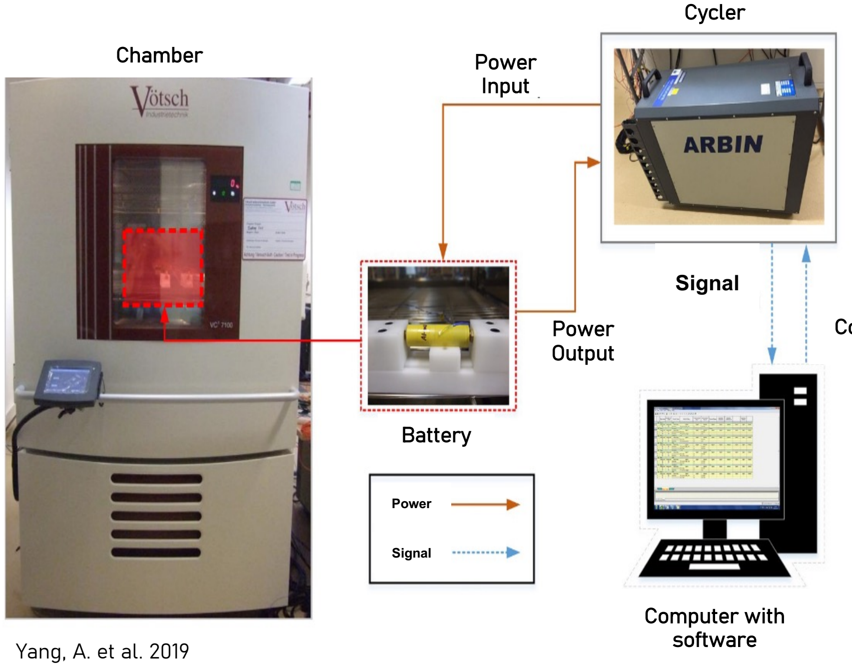
4 Crack propagation



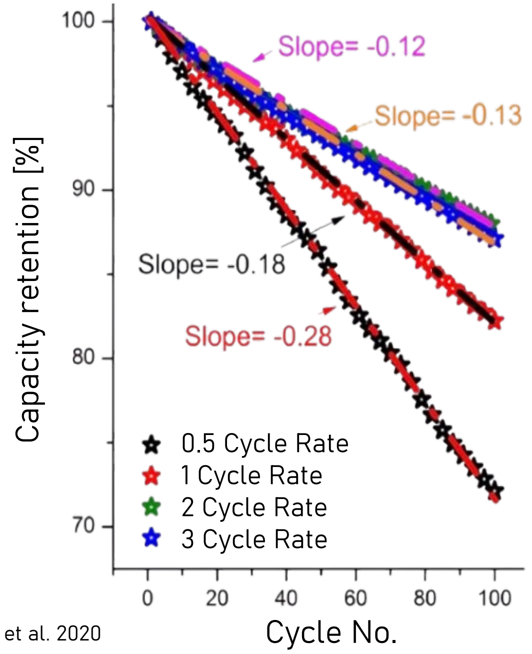
Molaeimanesh et al. 2018

Battery Degradation Rate

Experimental setup and degradation rate



Yang, A. et al. 2019



Ouyang et al. 2020

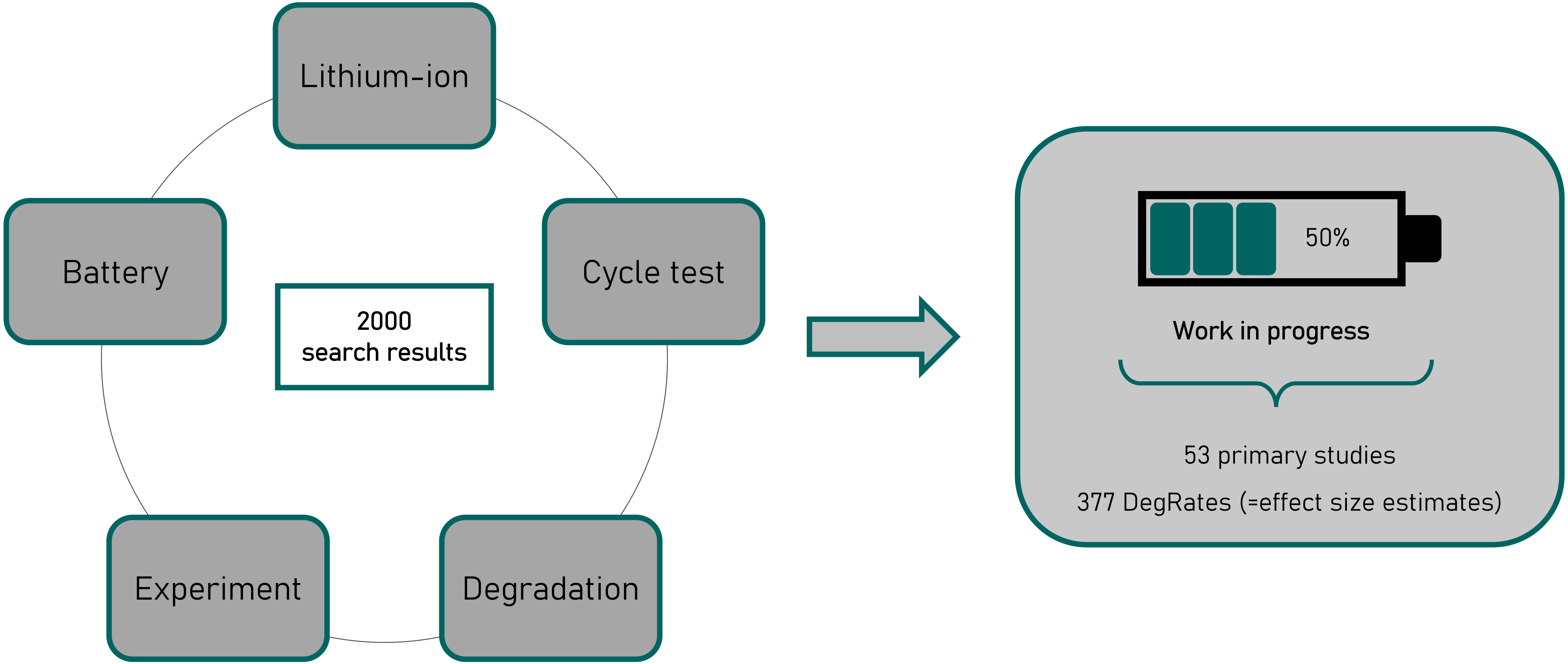
$$\text{DegRate} = \frac{C_0[\%] - C_{EoL}[\%]}{N_{cycle,EoL}}$$

Deng et al. 2024

C: Capacity
N: Cycle number

Literature research

Study selection



Methodological setup

Moderator variables

Publication characteristics

YEAR
CITATIONS
AUTHOR TYPE
SUPPORT COUNTRY

Battery differences

CATHODE
ANODE
NOMINAL CAPACITY
CELL SHAPE
CUTOFF VOLTAGES

Experimental differences

CHARGE/DISCHARGE PROTOCOL
CUTOFF VOLTAGES
DEPTH OF DISCHARGE
OVER(DIS)CHARGED
REST TIME
TEMPERATURE

Measurement characteristics

REFERENCE PERFORMANCE TEST
TEMPERATURE
KNOWN DEFECT

Methodological setup

Experimental research

Several factors, such as the experimental methodology or measurement approach, have an impact on the uncertainty in DegRate evaluation

Absence of standard error or other indicators of measurement uncertainties in the studies

Weighted least squares regression (WLS)

Model 1

Weighting with the inverse number of DegRate reported per study → Smaller weights for studies reporting many DegRates

Model 2

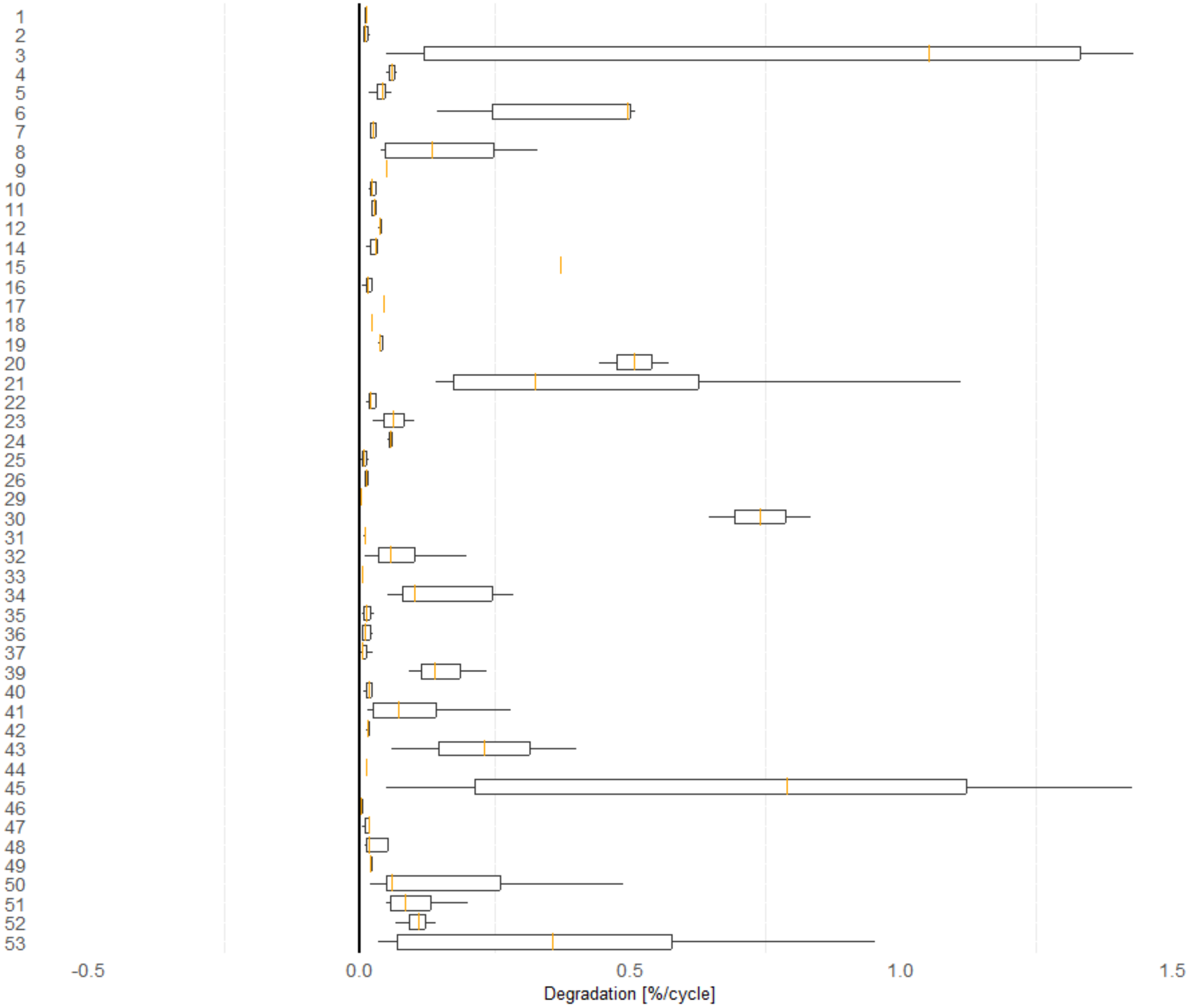
Weighting with developed quality indicator → Larger weights for more reliable measurements

Examples of penalization criteria to reflect study transparency and quality

- Cutoff Voltages of the experiment not reported
- Anode material not reported
- Lack of environmental chamber

Results

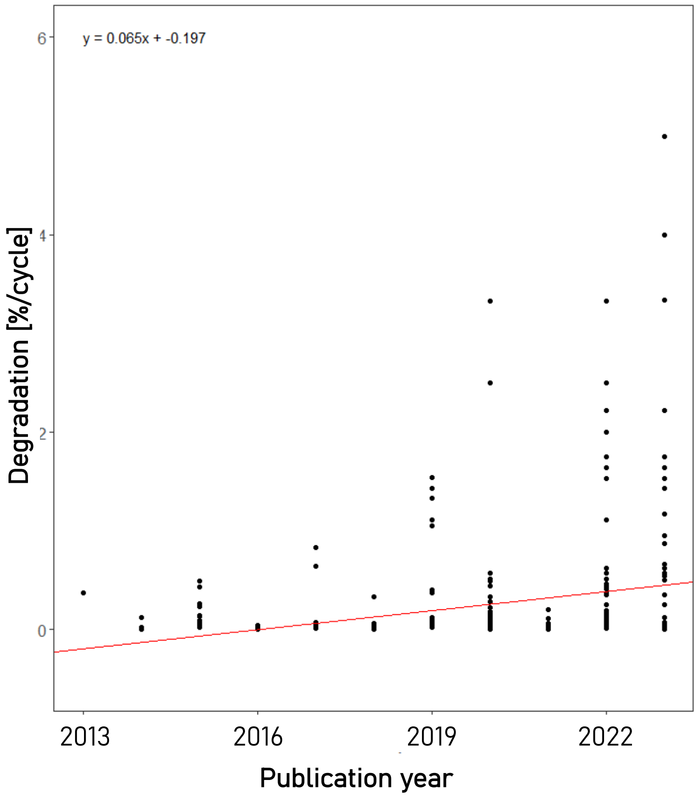
DegRates vary across studies

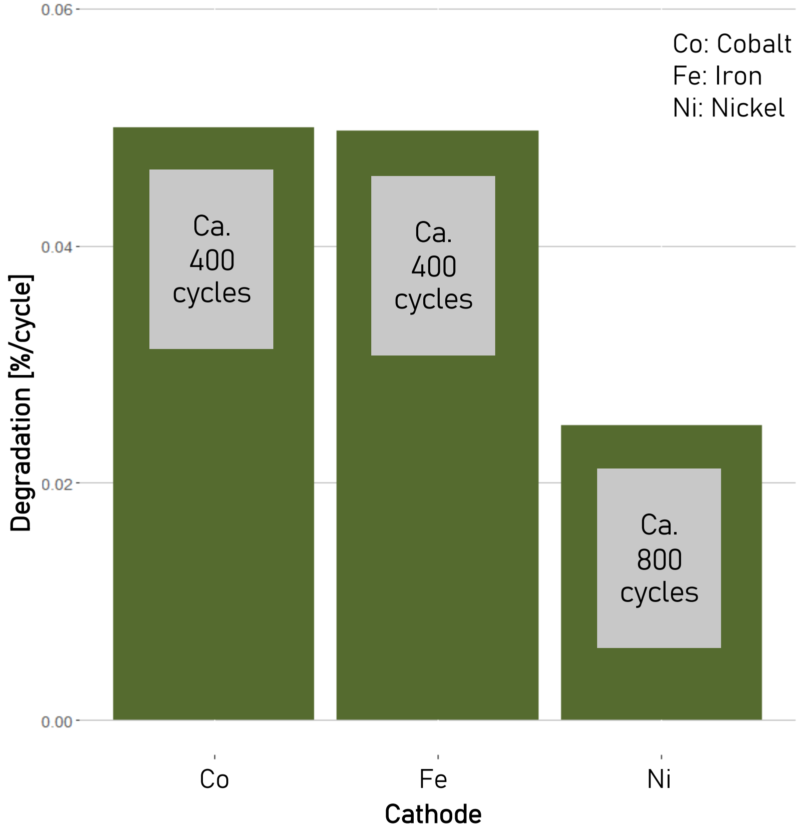


- Studies that cycled batteries at varying temperatures were excluded due to small number of cases
- For clear scaling, the x-axis was limited to 1.5, although studies report degradation over 5 %/cycle

Results

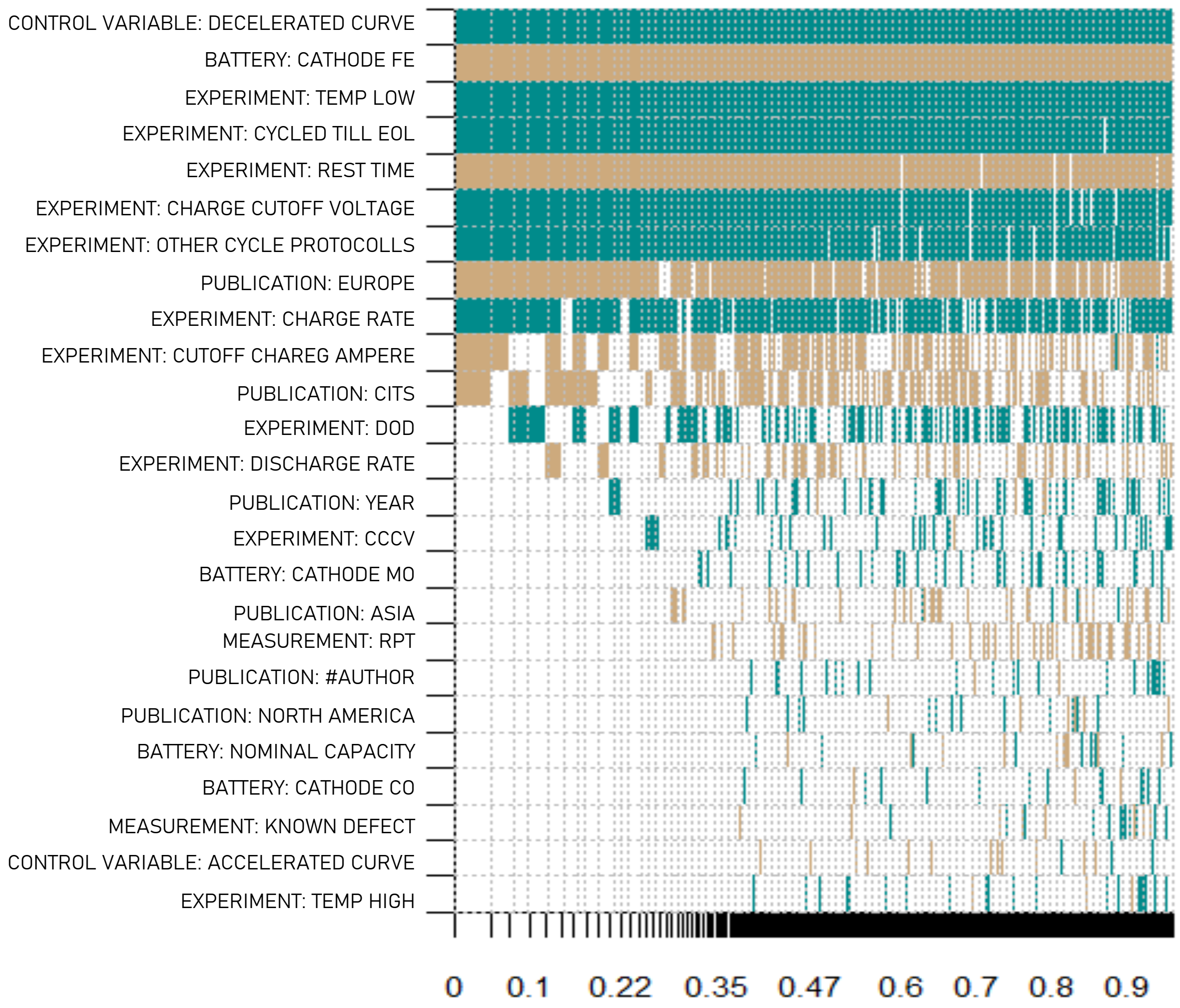
Descriptives





Results

BMA



Key findings of influencing factors

- **Temperature** is the main driver of battery degradation
- Different **cathode** materials contribute to the variation in DegRates
- **Country** supporting the study persue different interests
- Further experimental differences such as **rest time, cutoff charge voltage of experiment** and the **cycle protocol** prove to be important

Results

Regression

33 Studies / 240 observations	WLS MRA Model 1	WLS MRA Model 2	BMA PIP
Moderator variable			
INTERCEPT	-1.710*	**-2.259*****	1
Publication characteristics			
PUBLICATION: YEAR	**0.084****	0.096*	0.158
PUBLICATION: EUROPE[1]	-0.341	**-0.537*****	0.903
PUBLICATION: NORTH AMERICA[1]	0.071	0.360	0.067
PUBLICATION: ASIA[1]	-0.131	0.043	0.116
PUBLICATION: CITS	-0.851	-0.361	0.514
PUBLICATION: #AUTHOR	-0.005	0.019	0.070
Battery differences			
BATTERY: NOMINAL CAPACITY	-0.008*	-0.006	0.065
BATTERY: CATHODE CO[2]	0.060	0.042	0.064
BATTERY: CATHODE FE[2]	-0.451	**-1.171*****	1
BATTERY: CATHODE MO[2]	**0.892****	**1.254****	0.123
Measurement characteristics			
MEASUREMENT: RPT	-0.104	-0.068	0.105
MEASUREMENT: KNOWN DEFECT	-0.009	-0.204	0.059

33 Studies / 240 observations	WLS MRA Model 1	WLS MRA Model 2	BMA PIP
Moderator variable			
Experimental differences			
EXPERIMENT: CHARGE RATE	0.072	0.408	0.865
EXPERIMENT: DISCHARGE RATE	-0.013	-0.119	0.250
EXPERIMENT: CUTOFF CHAREG AMPERE	-0.109	-0.246	0.514
EXPERIMENT: DOD	0.184	0.134	0.426
EXPERIMENT: CYCLED TILL EOL	0.287*	**0.508*****	0.997
EXPERIMENT: CHARGE CUTOFF VOLTAGE	**0.063****	**0.130*****	0.985
EXPERIMENT: OTHER CYCLE PROTOCOLS[4]	0.442	**1.814*****	0.961
EXPERIMENT: CCCV[4]	-0.157	0.002	0.129
EXPERIMENT: REST TIME	-0.217*	**-0.563****	0.988
EXPERIMENT: TEMP LOW[3]	**1.198*****	**2.110*****	1
EXPERIMENT: TEMP HIGH[3]	-0.025	-0.032	0.054
Control variables			
CONTROL VARIABLE: DECELERATED CURVE[5]	0.226	**0.828****	1
CONTROL VARIABLE: ACCELERATED CURVE[5]	0.065	0.031	0.056

Note: Regression coefficients of the moderator variables. Standard errors of the regression coefficients are clustered at the level of the individual studies to accommodate within-study dependencies. ***, ** and * denote significance at the 1%, 5% and 10% level.
Base groups of the dummy variables: [1] none, [2] Cathode Nickel, [3] Temperature moderate, [4] CC Charge/Discharge, [5] linear curve

Conclusion

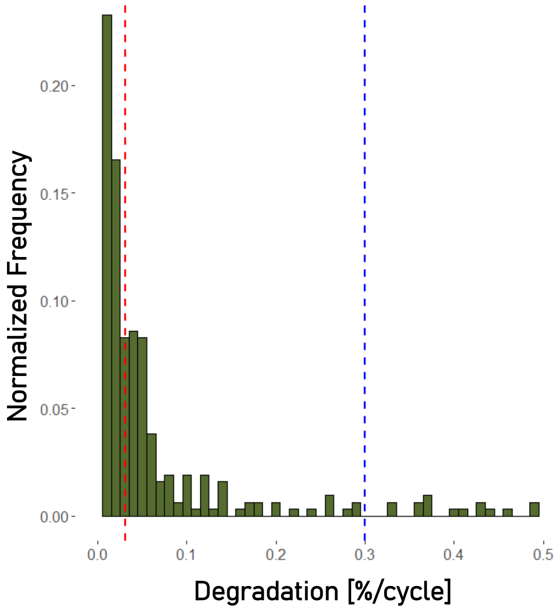
- Key findings
  - ➢ Experimental differences, especially temperature, drive battery degradation
  - ➢ Different cathode materials contribute to the variation in DegRates
  - ➢ The country supporting the study has an significant influence
- Prediction of european car driven in the winter

	Quality indicator	Average european car
Cycles	0.021 %/cycle = **952 cycles**	**1000 cycles**
Average consumption		21 kwh/100km
range [km]		160,000 km
Lifespan [year]		10 years

Conclusion

Challenges and Outlook

- Small dataset → coding still in progress
- Dealing with skewness



Median	Mean
0.031	0.299

- Decelerated curve
- Publication bias
- Expand literature search beyond Google Scholar (IEEE, Scopus, other databases

Thank you for your attention!

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FURTHER SLIDES

Why using Lithium-ion in battery thechnoloy

Comparison Parameter	Lead Acid	Nickel-Cadmium	Nickel Metal Hydride	Li-Ion
Compactness	–	–	–	+
Fast-charging process	+	+	+	+
Ease of disposal	+	+	+	–
Shelf life is more than 3 years	–	–	–	+
Memory effect	+	+	+	–
Permissible recharge	High	Average	Short	Very low
Depth of discharge (DOD)	50%	50–80%	50–85%	80%
Service intervals	3-6 months	30-60 days	60-90 days	Not regulated
Battery rated voltage [V]	2	1.2	1.2	3.7
Specific energy consumption [Wh/kg]	30–40	40–60	50–85	90–140
Specific power [W/kg]	180	150	250–1000	1800
Average charge time [h]	More than 10	8	6	2
Number of discharge (charge cycles)	500–800	2000	800	2000
Average self-discharge per month [%]	4	20	30	7
Average cost per kWh [$]	150	400–800	250	450

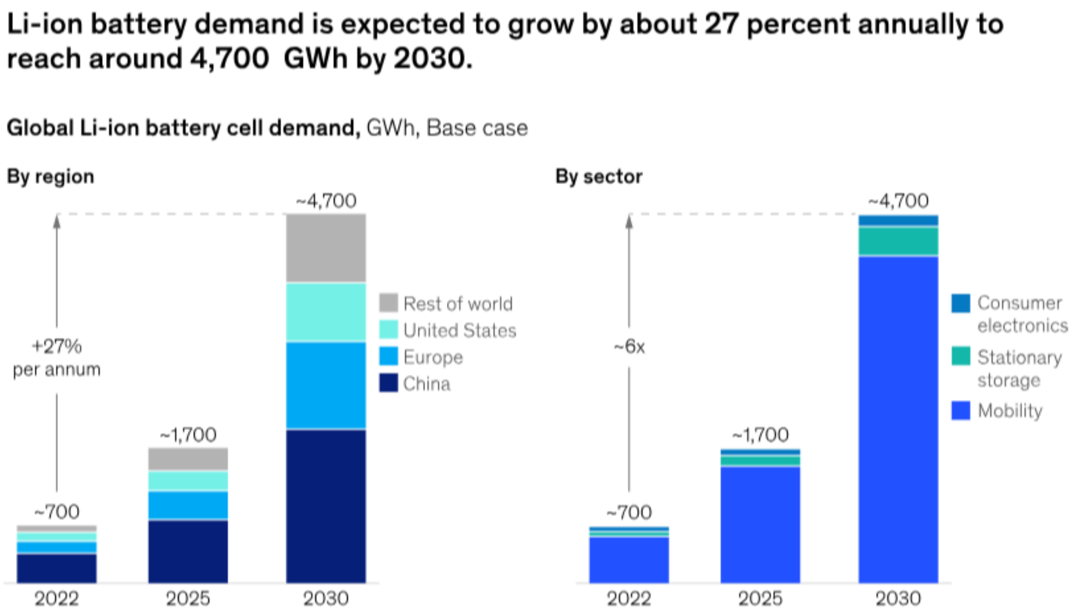
Shchurov et al. 2021

	2010s		2020s		2030s	
1 Cathode	LCO[1]	LMO[2] LFP[3] NMC[4]/NCA[5]	LFP[3] NMC[4]/NCA[5]	LFP[3] NMC[4]/NCA[5] LMFP[6]/LMNO[7]	NMC[4]/NCA[5] LMFP[6]/LMNO[7] Sulphur	LMFP[6]/LMNO[7] Sulphur
2 Separator/ electrolyte	Polymer/liquid	Polymer/liquid	Polymer/liquid	Polymer/liquid	Polymer/liquid Advanced liquid Semi-solid	Advanced liquid Semi-solid Solid
3 Anode	Graphite	Graphite	Graphite	Graphite Graphite and silicon	Graphite and silicon Lithium metal Silicon anode	Lithium metal Silicon anode
4 Casing	Cylindrical	Cylindrical Pouch	Prismatic Cylindrical Pouch	Prismatic Cylindrical Pouch	Cylindrical Pouch Prismatic	Cylindrical Pouch

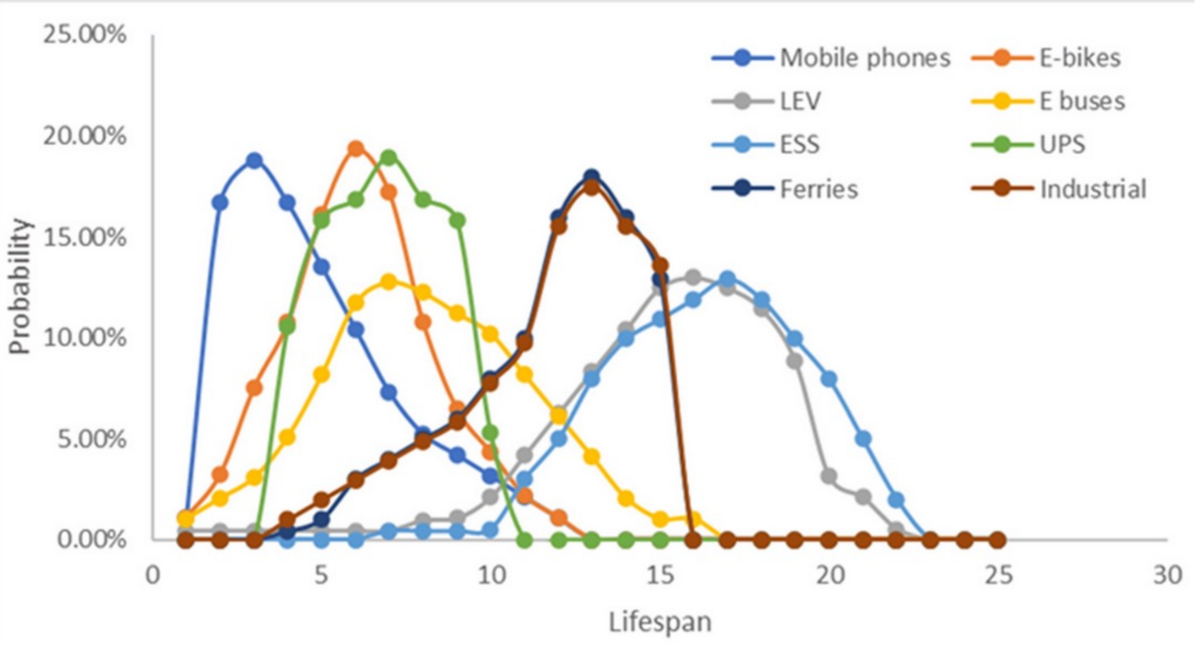
[1]Lithium cobalt.
[2]Lithium manganese oxide.
[3]Lithium, iron, phosphate.
[4]Lithium, manganese cobalt.
[5]Lithium, nickel, cobalt, aluminum oxide.
[6]Lithium manganese iron phosphate.
[7]Lithium, manganese nickel oxide.
Source: McKinsey Battery Insights, 2022

Fleischmann et al. 2023

Lifespan

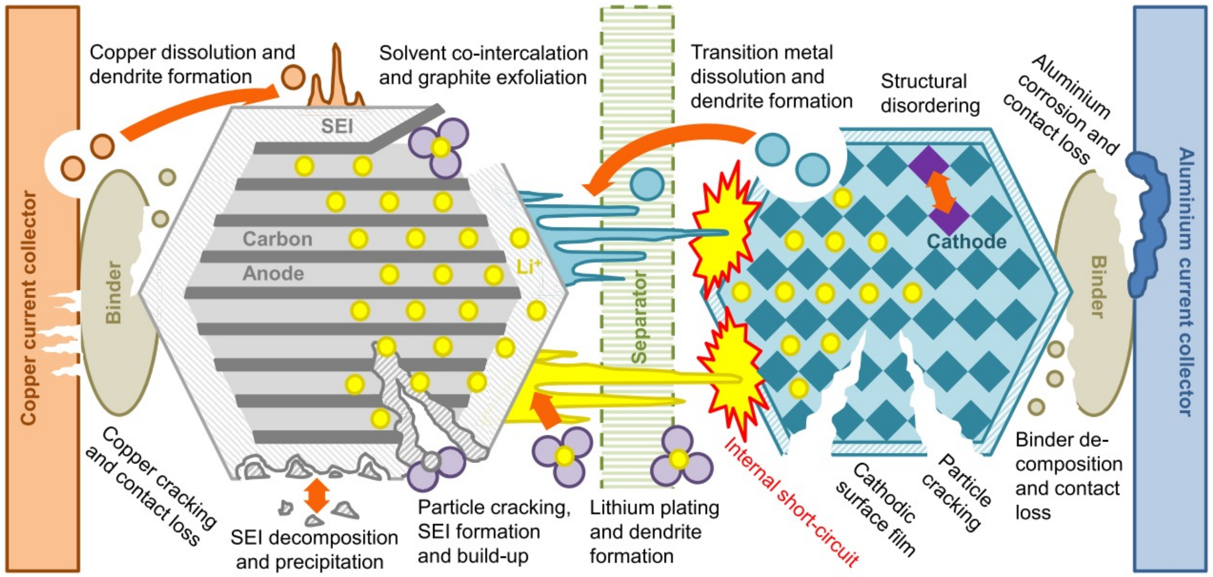


Fleischmann et al. 2023

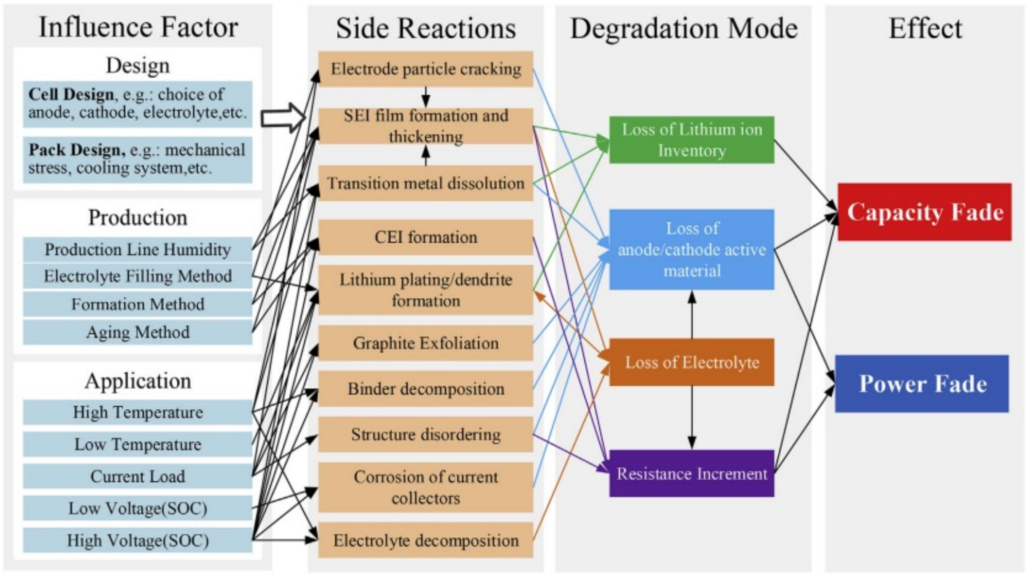


Gaines 2023

Degradation of Lithium-Ion Batteries

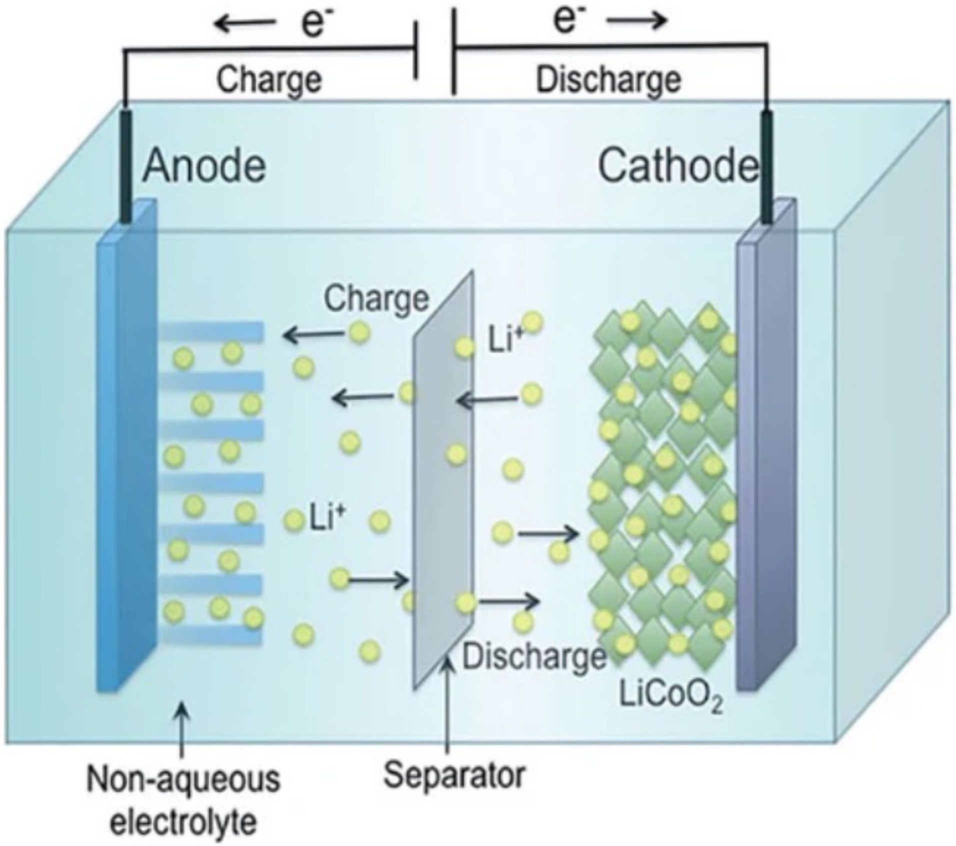


Birkl et al. 2017



Han et al. 2019

Schematic diagram of the working principle of lithium-ion battery



Problem

Experimental research vs. Observational research

Experimental research

Systematic manipulation of one or more independent variables to observe their effects on a dependent variable

Example:
Measuring the degradation rate of a specific photovoltaic system under known circumstances

↓

Statistical parameters such as the variance are difficult to determine and are not always given

Observational research

Observing the relationship between two or more variables without manipulating them

Example:
Regression analysis of the relationship between shareholder activism and the shareholder return

↓

Statistical parameter such as the variance are frequently addressed and given

Meta-regression analysis

Meta-regression analysis after Stanley and Jarrell 1989

Application in experimental research

$$DR_{ij} = \beta_0 + \sum_{k=1}^{K} \gamma_{ij} Z_{ijk} + \varepsilon_{ij},\ \varepsilon_{ij} \sim N\left(0; \sigma^2_{DR_{ij}}\right)$$

DR_{ij} annual DR of the ith estimate taken from the jth study

γ_{ij} meta-regression coefficients

Z_{ijk} set of k moderator variables

ε_{ij} error term

No standard error of the DR estimate

Weighted least squares regression (WLS) to adress the heteroscedasticity observed in the residuals

Model 1
Weighting with the inverse number of DR estimates reported

↓

Assign smaller weight to studies reporting many DR estimates

Model 2
Weighting with constructed reliability metic

↓

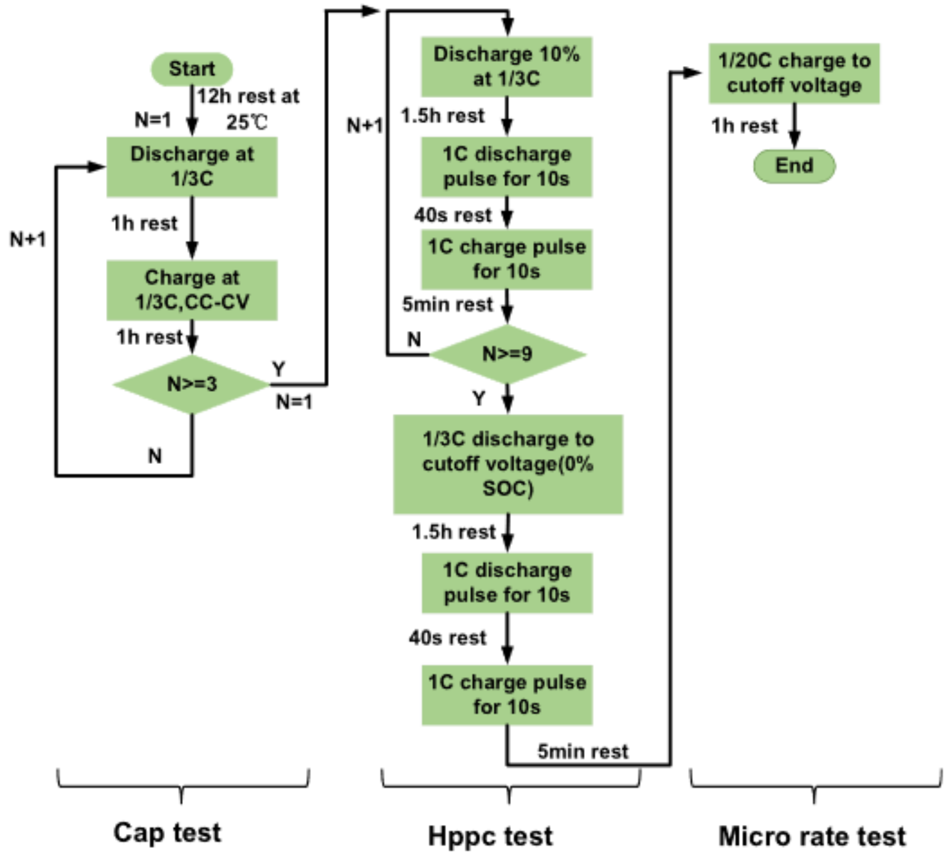
Assign larger weight to more reliable DR estimates

Clustered standard errors

Clustering at study level to account for within-study dependencies and avoid misleadingly precise estimates

Meta-analysis

Methodological differences



Reference Performance Test (Wu 2020)

Results

Regression

Moderator variable	Description
Publication characteristics	
PUBLICATION: YEAR	Natural logarithm of publication year of the study – 2006
PUBLICATION: EUROPE[1]	=1, if the country suporting the study is an European country
PUBLICATION: NORTH AMERICA[1]	=1, if the country supporting the study is a North American country
PUBLICATION: ASIA[1]	=1, if the country supporting the study is an Asian country
PUBLICATION: CITS	Natural logarithm of the annual citations of the study
PUBLICATION: #AUTHOR	Natural logarithm of the author number
Battery differences	
BATTERY: NOMINAL CAPACITY	Natural logarithm of the nominal capacity
BATTERY: CATHODE CO[2]	=1, if the cathode material contains cobalt
BATTERY: CATHODE FE[2]	=1, if the cathode material contains iron
BATTERY: CATHODE MO[2]	=1, if the cathode material contains manganese oxide
Measurement characteristics	
MEASUREMENT: RPT	=1, if the capacity was determined by reference performance test
MEASUREMENT: KNOWN DEFECT	=1, if the study reports any known defect, 0 otherwise

Moderator variable	Description
Experimental differences	
EXPERIMENT: CHARGE RATE	Natural logarithm of the charge rate
EXPERIMENT: DISCHARGE RATE	Natural logarithm of the discharge rate
EXPERIMENT: CUTOFF CHARGE AMPERE	Natural logarithm of cutoff charge ampere
EXPERIMENT: DOD	Natural logarithm of the depth of discharge
EXPERIMENT: CYCLED TILL EOL	=1, if the battery has been cycled to at least 80% of its capacity
EXPERIMENT: CHARGE CUTOFF VOLTAGE	Natural logarithm of charge cutoff voltage
EXPERIMENT: OTHER CYCLE PROTOCOLS[4]	=1, if special cycle protocols (e.g. UDDS or DST) were used
EXPERIMENT: CCCV[4]	=1, if constant charging constant voltage protocol was used
EXPERIMENT: REST TIME	=1, if there is a rest time between the charging and discharging phases
EXPERIMENT: TEMP LOW[3]	=1, if the temperature is between -20°C and 10°C
EXPERIMENT: TEMP HIGH[3]	=1, if the temperature is between 40°C and 70°C
Control variables	
CONTROL VARIABLE: DECELERATED CURVE[5]	=1, if the degradation curve has a decelerating shape
CONTROL VARIABLE: ACCELERATED CURVE[5]	=1, if the degradation curve has a accelerated shape

Base groups of the dummy variables: [1] none, [2] Cathode Nickel, [3] Temperature moderate, [4] CC Charge/Discharge, [5] linear curve

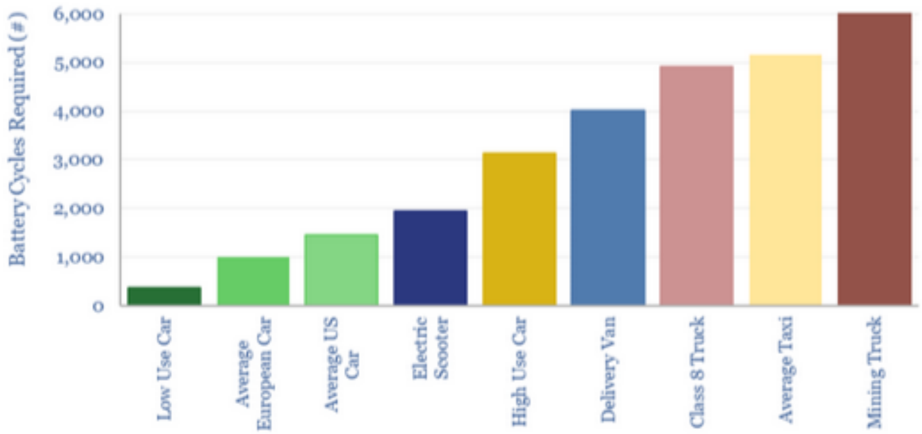
Quality Indicator

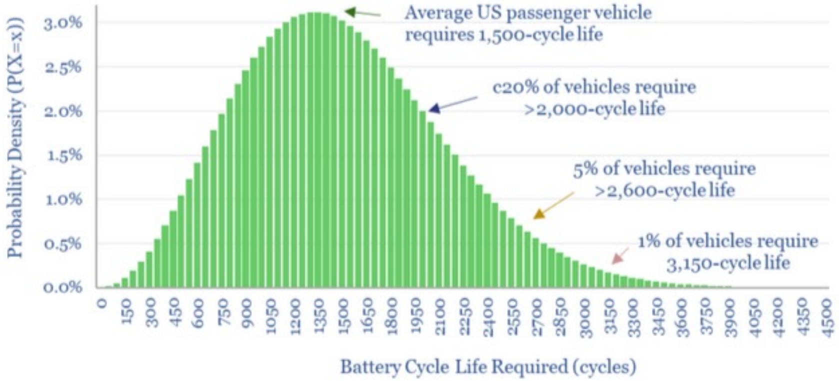
Penalizing scheme

Quality indicaot	Penalty point
cutoff charge voltage of experiment not reported	2
cutoff discharge voltage of experiment not reported	2
Cycle equipment not reported	2
temperature control device not used	2
Reference performance test not used	2
SOC (min) not reported	2
SOC (max) not reported	2
DOD not reported	2
Anode not reported	1
charge cutoff voltage provided by manufacturer not reported	1
discharge cutoff voltage provided by manufacturer reported	1
Battery size not reported	1
$\sum$	20

Results

Descriptives

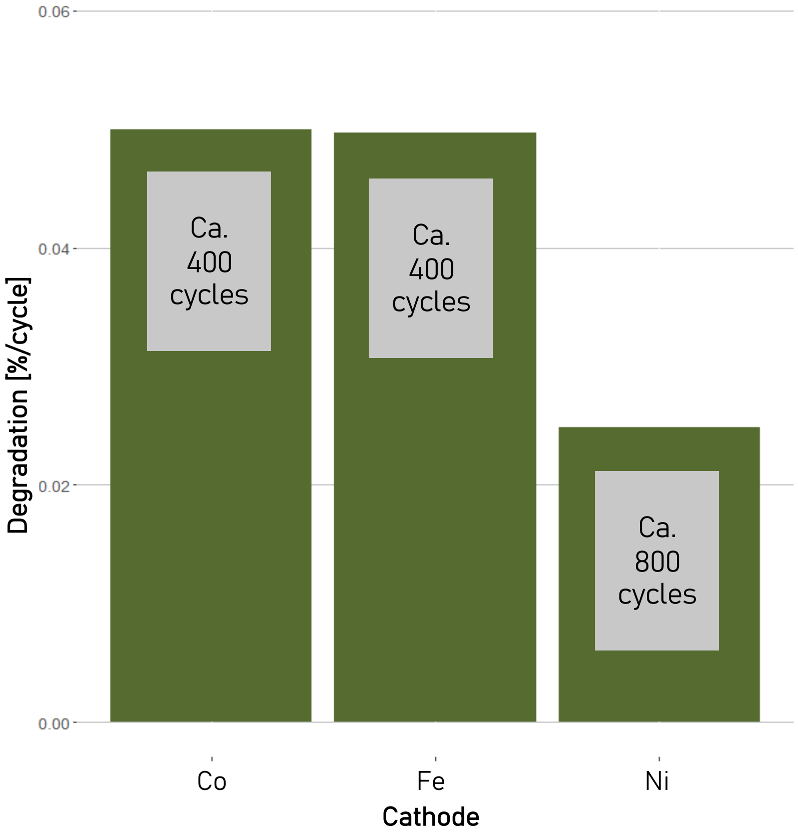


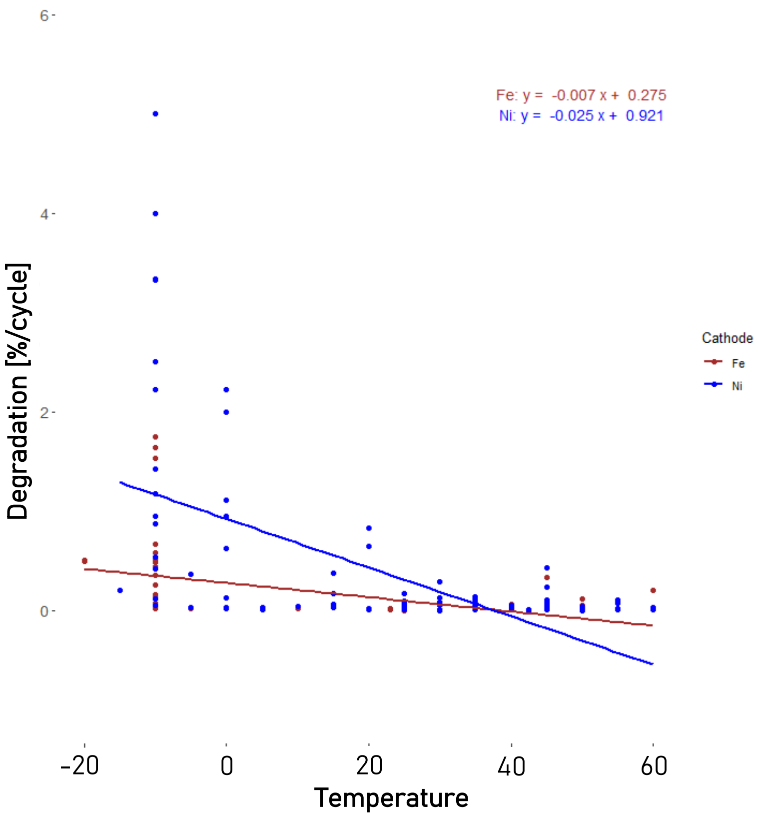


https://thundersaidenergy.com/downloads/electric-vehicle-battery-life/

Backup Folie

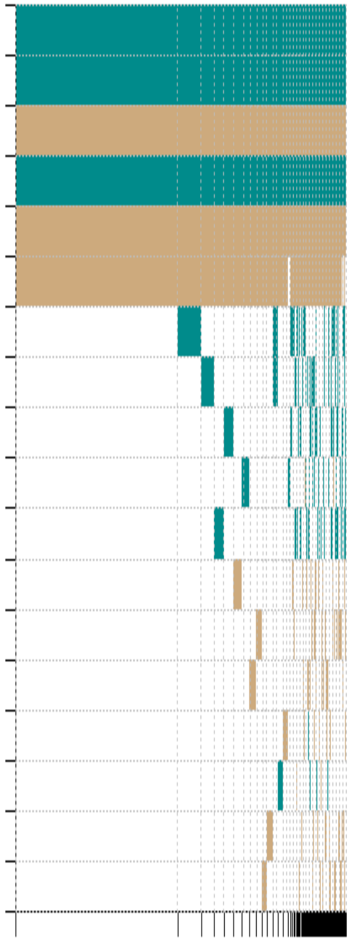
Warum LFP höhere DegRate hat wenn man es alleine betrachtet aber unter Berücksichtigung der temperatur nicht, da sehr Temperatur anfällig





Results

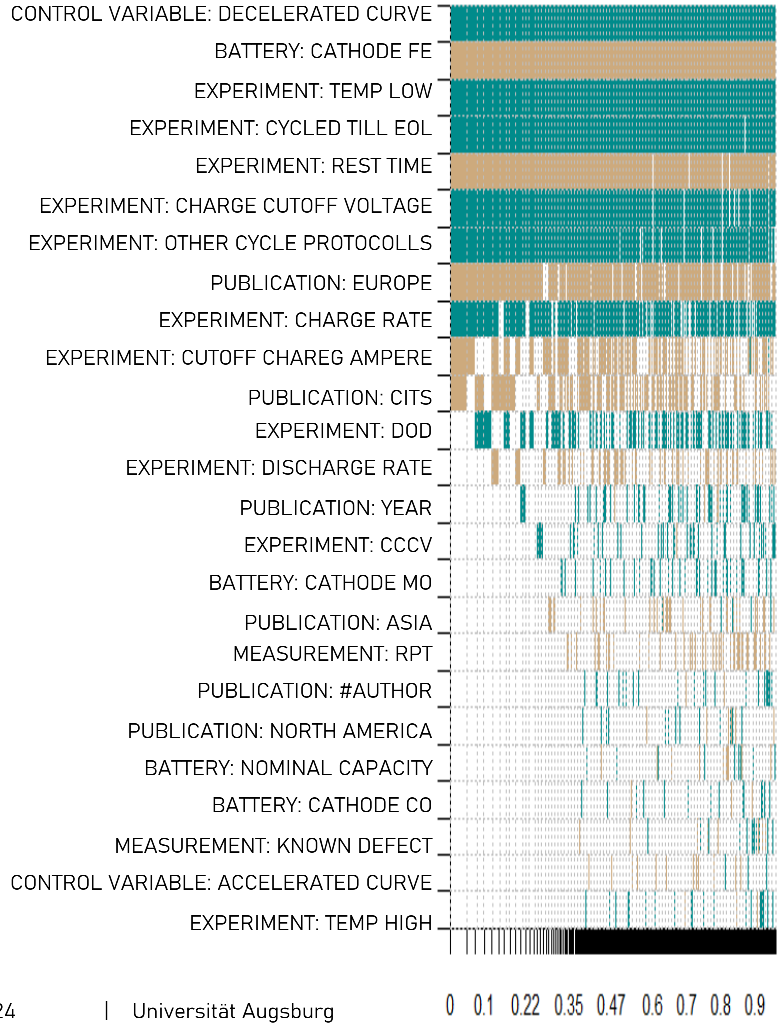
BMA + Regression – all Study IDs



49 Studies/355 DegRates	WLS MRA		BMA
	Model 1	Model 2	PIP
Moderator variable			
INTERCEPT	-0.034	-0.470	1
Publication characteristics			
PUBLICATION: CITS	**-2.756****	-2.711*	0.993
PUBLICATION: EUROPE[1]	**-0.325****	**-0.853*****	0.979
PUBLICATION: ASIA[1]	-0.045	-0.120	0.065
PUBLICATION: NORTH AMERICA[1]	-0.032	-0.456	0.045
PUBLICATION: #AUTHOR	-0.001	0.025	0.038
PUBLICATION: YEAR	0.005	0.019	0.039
Battery differences			
BATTERY: CATHODE FE[2]	**-0.397****	**-0.928*****	1
BATTERY: CATHODE CO[2]	0.046	0.094	0.068
BATTERY: CATHODE MO[2]	-0.094	0.169	0.037
Experimental differences			
EXPERIMENT: CYCLED TILL EOL	**0.373*****	**0.714*****	1
EXPERIMENT: TEMP LOW[3]	**1.044*****	**1.365*****	1
EXPERIMENT: OTHER CYCLE PROTOCOLLS[4]	0.250	0.423**	0.099
EXPERIMENT: CCCV[4]	-0.004	-0.017	0.046
EXPERIMENT: TEMP HIGH[3]	0.028	-0.049	0.037
Measurement characteristics			
MEASUREMENT: KNOWN DEFECT	0.128	0.051	0.145
MEASUREMENT: RPT	-0.003	0.142	0.064
Control variables			
CONTROL VARIABLE: DECELERATED CURVE[5]	**0.275****	**0.723****	1
CONTROL VARIABLE: ACCELERATED CURVE[5]	-0.094	-0.092	0.056
R^2 (adjusted)	0.34 (0.30)	0.55 (0.53)	

Results

BMA + Regression – alle moderators



33 Studies/ 240 DegRates	WLS MRA		BMA
	Model 1	Model 2	PIP
Moderator variable			
INTERCEPT	-1.710*	**-2.259*** **	1
Publication characteristics			
PUBLICATION: YEAR	**0.084***	0.096*	0.158
PUBLICATION: EUROPE	-0.341	**-0.537*****	0.903
PUBLICATION: CITS	-0.851	-0.361	0.514
PUBLICATION: NORTH AMERICA	0.071	0.360	0.067
PUBLICATION: ASIA	-0.131	0.043	0.116
PUBLICATION: #AUTHOR	-0.005	0.019	0.070
Battery differences			
BATTERY: NOMINAL CAPACITY	-0.008*	-0.006	0.065
BATTERY: CATHODE CO	0.060	0.042	0.064
BATTERY: CATHODE FE	-0.451	**-1.171*****	1
BATTERY: CATHODE MO	**0.892****	**1.254****	0.123
Experimental differences			
EXPERIMENT: CHARGE RATE	0.072	0.408	0.865
EXPERIMENT: DISCHARGE RATE	-0.013	-0.119	0.250
EXPERIMENT: CCCV	-0.157	0.002	0.129
EXPERIMENT: CYCLED TILL EOL	0.287*	**0.508*****	0.997
EXPERIMENT: CHARGE CUTOFF VOLTAGE	**0.063****	**0.130*****	0.985
EXPERIMENT: CUTOFF CHAREG AMPERE	-0.109	-0.246	0.514
EXPERIMENT: DOD	0.184	0.134	0.426
EXPERIMENT: OTHER CYCLE PROTOCOLLS	0.442	**1.814*****	0.961
EXPERIMENT: REST TIME	-0.217*	**-0.563****	0.988
EXPERIMENT: TEMP LOW	**1.198*****	**2.110*****	1
EXPERIMENT: TEMP HIGH	-0.025	-0.032	0.054
Measurement characteristics			
MEASUREMENT: RPT	-0.104	-0.068	0.105
MEASUREMENT: KNOWN DEFECT	-0.009	-0.204	0.059
Control variables			
CONTROL VARIABLE: DECELERATED CURVE	0.226	**0.828****	1
CONTROL VARIABLE: ACCELERATED CURVE	0.065	0.031	0.056
R^2 (adjusted)	0.40 (0.33)	0.73 (0.70)	

The most important contributions:

M. Stanley Whittingham: He developed the first concept of a rechargeable lithium battery 1970 with a lithium metal anode and a titanium disulphide cathode.

John B. Goodenough: He discovered the high-performance cathode material lithium cobalt oxide ($LiCoO_2$) in 1980, which increased the voltage and energy density of the battery.

Akira Yoshino: He developed the first safe and commercially viable lithium-ion battery by using graphite as the anode material in 1985 based on Goodenougs LCO cathode material

SONY: First commercial LIB in 1990 (LCO + Graphite) based on Yoshinos work