Lifetime predictions of the lithium ion batteries in the Virtual Power Plant

by
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Dansk Batteri Selskab Møde

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OUTLINE

- **Background, VPP concept, services**
- **Lifetime predictions - cell level**
  - **Li-ion battery performance modeling**
  - **Accelerated lifetime tests and Li-ion battery ageing model**
  - **Lifetime and economical analyses for the selected services**
- **Lifetime predictions – system level**
- **Conclusions**

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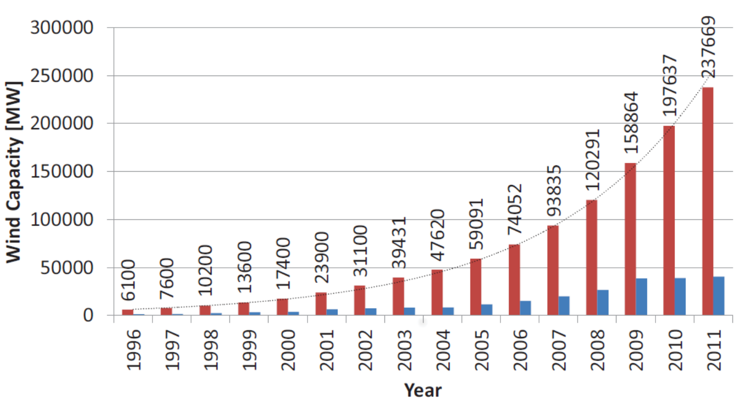
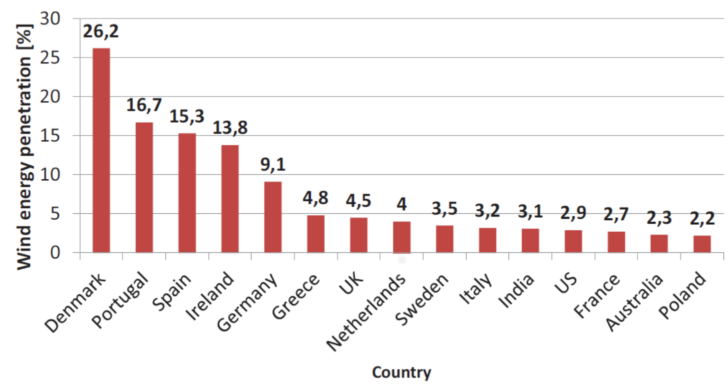
Background

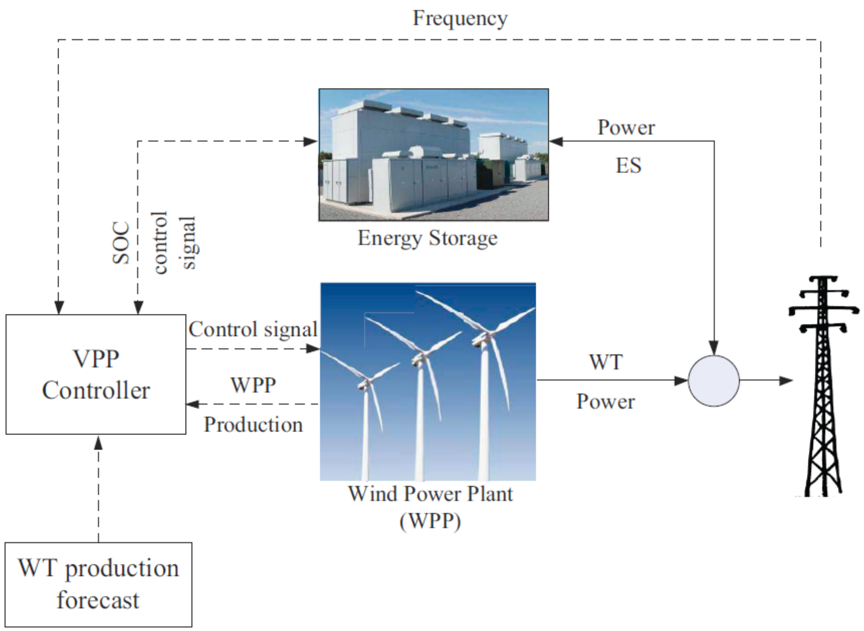
- High penetration of the wind energy in certain grids
- Variable and partly unpredictible wind resource
- Technical (power system balance) and economical difficulties (higher cost of WT integration in the grid) in grids with high wind penetration
- Future WPPs need to behave similar to the conventional generation units...
- ... and be ready for the future more stringent grid codes





Virtual Power Plant concept

- High wind penetration in the grid will require higher flexibility from the wind industry and better production accuracy
- Energy Storage System (ESS) as a controllable energy buffer
- Virtual Power Plant (VPP)- Wind Power Plant (WPP) with a high control capability
- VPP has a behaviour and capability similar to the conventional generation units



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Li-ion Batteries + Services

Services that supports WT/WPP

- Wind power forecast accuracy improvement
- WT/WPP output power gradient reduction
- Inertia emulation
- Grid frequency support
- Voltage control support

Ancillary services

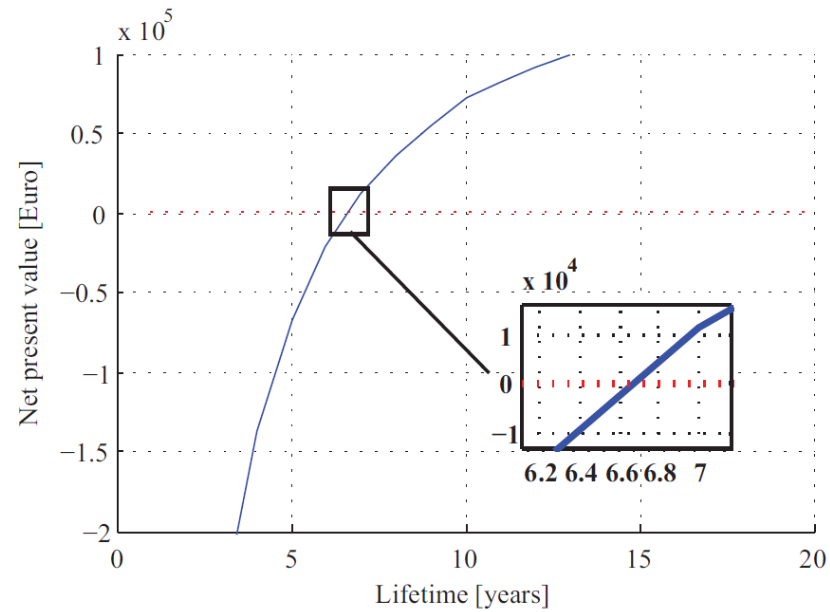
- Black start
- Energy arbitrage
- Peak shaving
- Load following
- Transmission enhancment deferring
- Spinning reserve
- Power quality

Li-ion batteries:

- long cycle and calendar lifetime
- the highest electrical round-trip efficiency
- fast reaction time
- low self-discharge
- low O&M cost
- rapid development and high potential for the product improvement
- relatively mature

Need for ESS performance and lifetime models

- ✓ Important for investment profitability calculations.
- ✓ Performance is lifetime dependent.
- ✓ Accurate reliability design
- ✓ Complex process of cell degradation. Lot of factors influencing life time.
- ✓ Difficulties in predicting lifetime under complex cycling profile which are characteristic for VPP services.



Simulation parameters: storage size: 0.4MW/0.1MWh, storage price: 700€/kWh, power electronic cost: 100€/kW, revenues per year: 20k€, interest rate: 5%.

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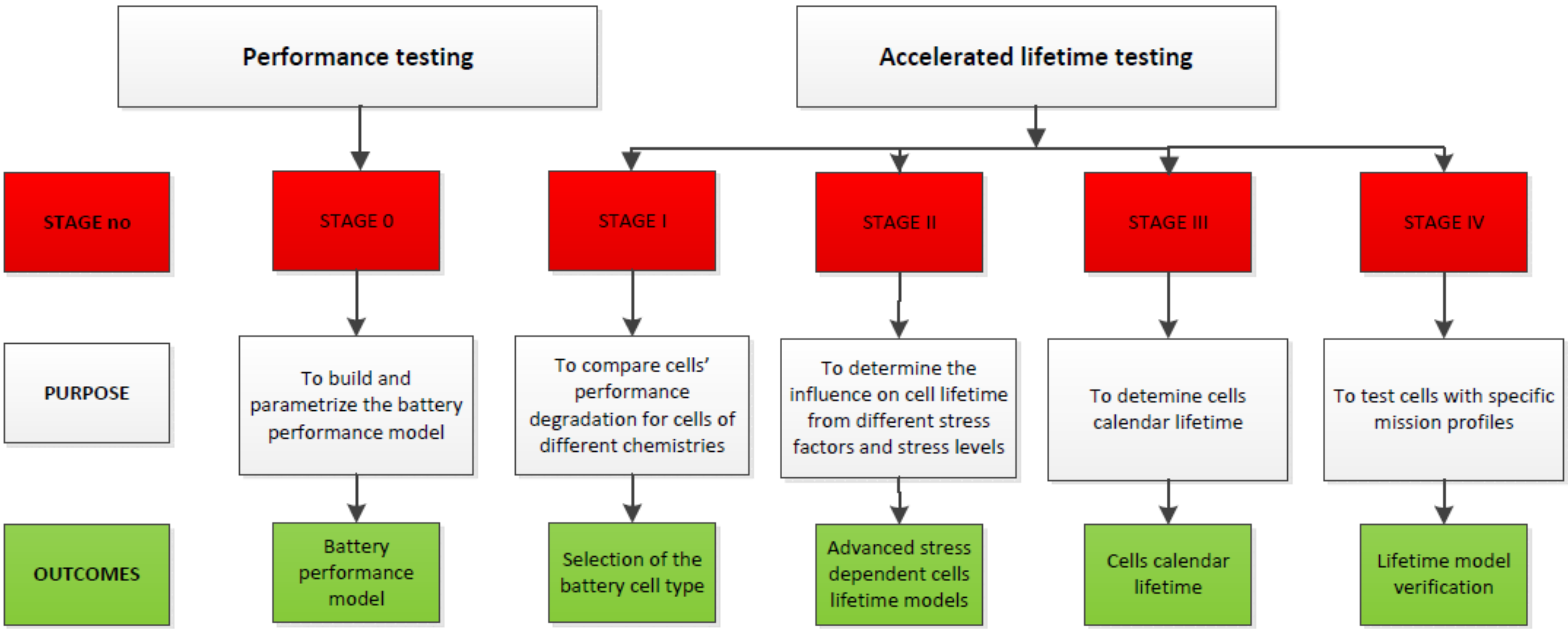
Methodology

Laboratory experiments



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Li-ion BESS for stationary applications

- Many Li-ion battery chemistries are currently available and each of them has its own characteristics and limitations
- The most important parameters for considered services are low cost per cycle, fast response, low self-discharge and safety
- LFP and LTO are promising cathode/anode materials for the stationary applications

Cathode material	Property	Anode material	Property
$LiCoO_2$ (LCO)	long lifetime, low safety, high specific energy	Graphite LiC_6	3.7 V, expensive, long cycle life
$LiFePO_4$ (LFP)	3.3 V, intrinsically safe, long lifetime, inexpensive, higher self-discharge than other Li-ion types	Hard carbon LiC_6	3.7 V, short cycle life
$LiMn_2O_4$ (LMO)	safer and cheaper than $LiCoO_2$ and $LiNiO_2$	Titanate $Li_4Ti_5O_{12}$ (LTO)	2.2V, safe, long lifetime, good low temperature performancelower energy density
$LiNiCoAlO_2$ (NCA)	high energy, power density and lifetime, least safe, high cost	Silicium $Li_{22}Si_6$	3.7 V, currently under development, high energy density
$LiNiMnCoO_2$ (NMC)	very popular, degrees of freedom for optimizing, different doping and wide variability of performance, low self-heating rate		

Parameter	Li-ion battery chemistry					
	Cathode material					*Anode material*
	LCO_2	NMC	NCA	LMnO	LFP	LTO
Lifetime	-	+	++	-	++	++
Cost per cycle	+	+	-	+	++	++
Fast response	++	++	++	++	++	++
Performance	+	+	+	-	+	++
Safety	-	+	-	+	++	++
Self-discharge	++	++	++	++	+	++

Legend: ++ very good performance, + good performance, - low performance, −− very low performance

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Li-ion cells under test

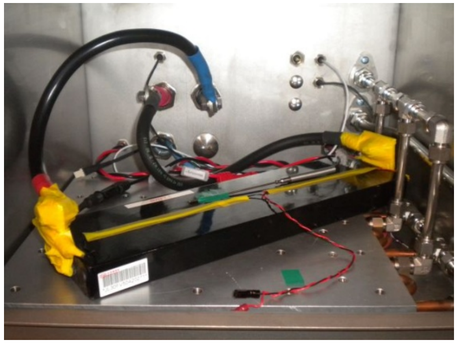
Battery Test Station

Type	Chemistry	Nominal capacity [Ah]	Nominal voltage [V]
1A	$LiFePO_4/C$	2.3	3.3
2	$LiFePO_4/C$	50	3.2
3	$LMO2/Li_4Ti_5O_{12}$	50	2.3

Cylindrical (type 1)

Pouch (type 2)

Prismatic (type 3)



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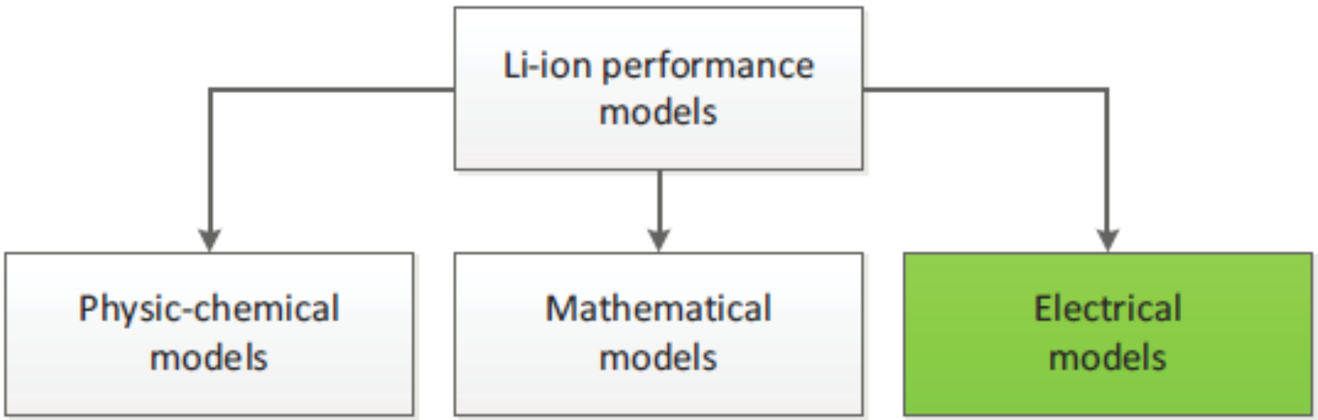
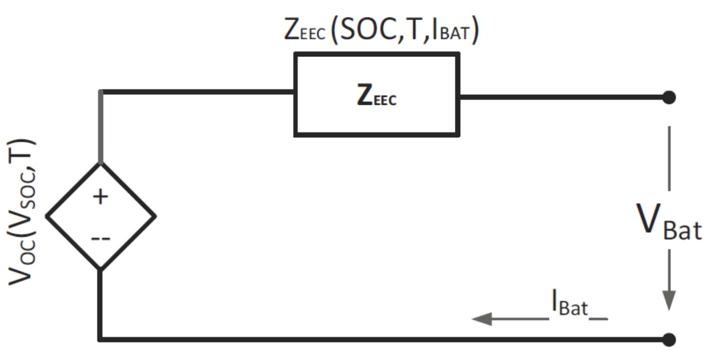
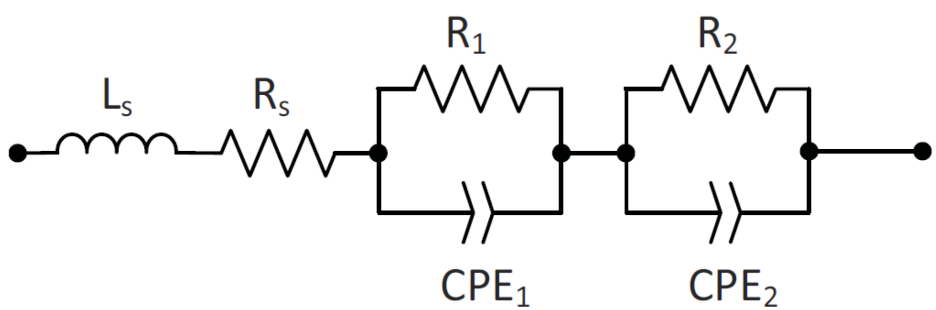
Li-ion batteries performance modelling





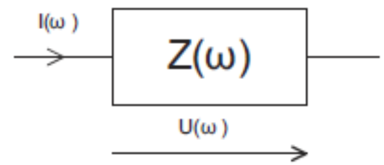


$$Z_{EEC_{ZARC}} = j\omega L_s + R_s + \frac{1}{\frac{1}{R_1} + (j\omega)^{n_1} Q_1} + \frac{1}{\frac{1}{R_2} + (j\omega)^{n_2} Q_2}$$

Electrochemical Impedance Spectroscopy

determination of the battery cell Nyquist characteristics by means of small signal AC impedance measurements at certain temperatures and SOCs

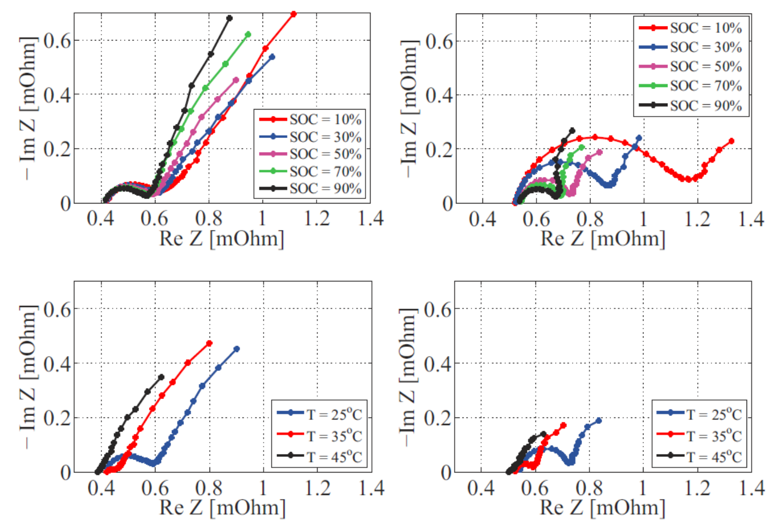
$$Z = \frac{U \sin(\omega t)}{I \sin(\omega t - \phi)}$$



- non-destructive measurement

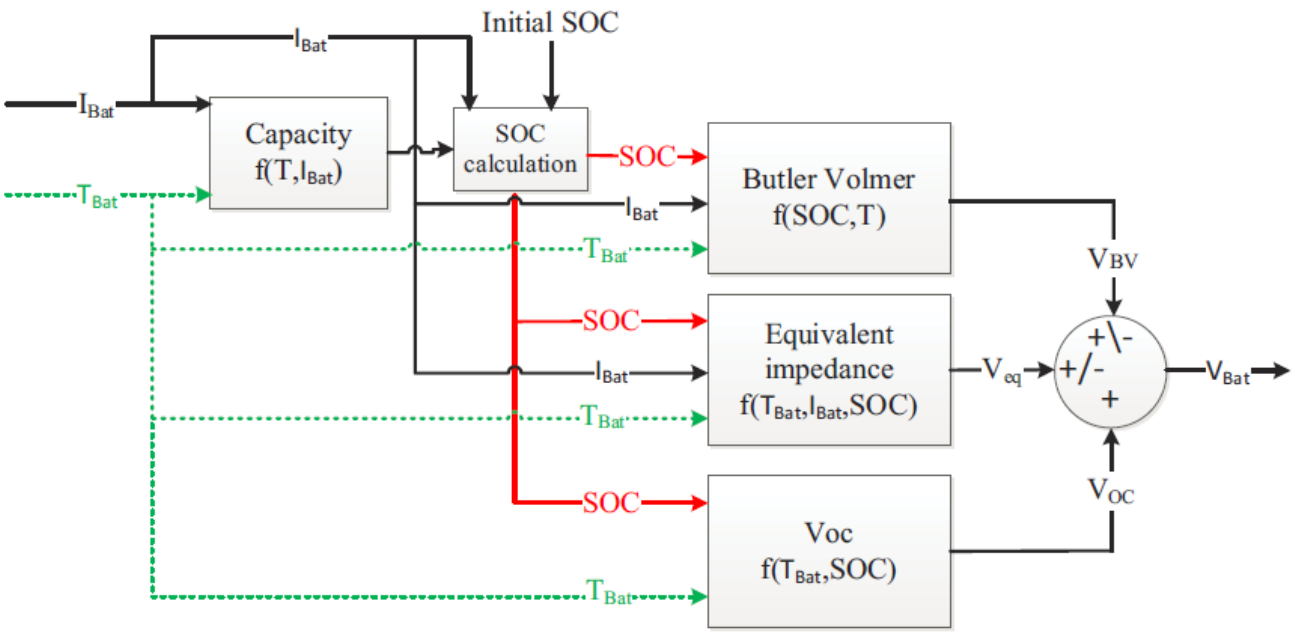
EIS measurements can be used for:

- Model parameterization.
- Non-destructive identification of the battery cells lifetime degradation.
- Identification of the differences between the cells.
- It can be used also for losses calculation and heat generation of the battery cells.



$LiFePO_4/C$ $LMO2/Li_4Ti_5O_{12}$

Li-ion batteries performance modelling



$$V_{Bat} = V_{EQULIBRIUM} \pm V_{OHMIC} \pm V_{CH.TRANSFER} \pm V_{DIFFUSION}$$

$$V_{Bat} = V_{OC} + I_{Bat} \cdot \left(j\omega L_s + R_s + \frac{1}{\frac{1}{R_2} + (j\omega)^{n_2} Q_2} + V_{BV}\right)$$

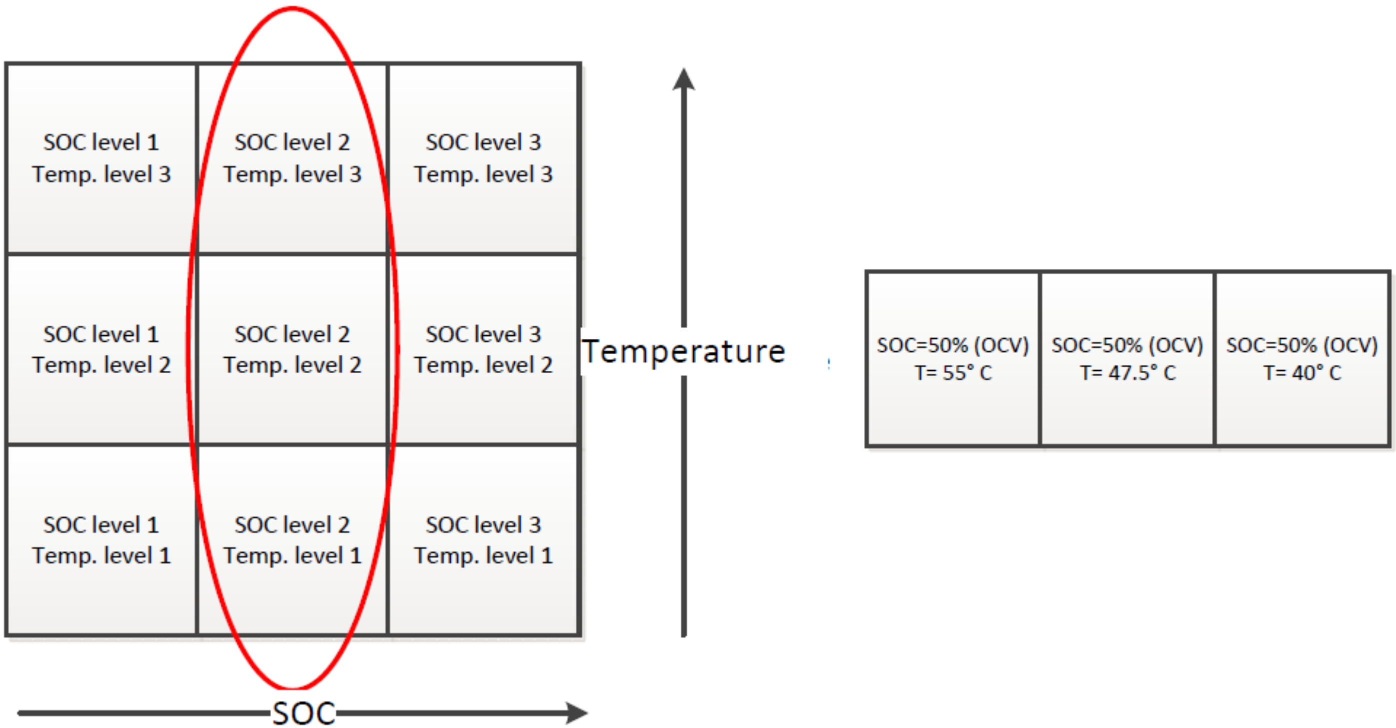
$$V_{BV} = \frac{R \cdot T}{\alpha \cdot F} \ln\left(\left|\frac{I_{Bat}}{A \cdot i_0}\right|\right)$$ Butler Volmer

Li-ion battery ageing

- Lithium-ion batteries are complex systems and the processes of their ageing are even more complicated
- Capacity decrease and power fading do not originate from one single cause but from a number of various processes and their interactions
- It does not exist general set of phenomena which is valid for all lithium ion cells and many ageing phenomena are chemistry dependent
- In general ageing of lithium ion cells is caused by time (calendar) and use (cycle)
- Ageing is caused by side reactions which could be accelerated by certain stress factors (like temperature, DOD, etc.)

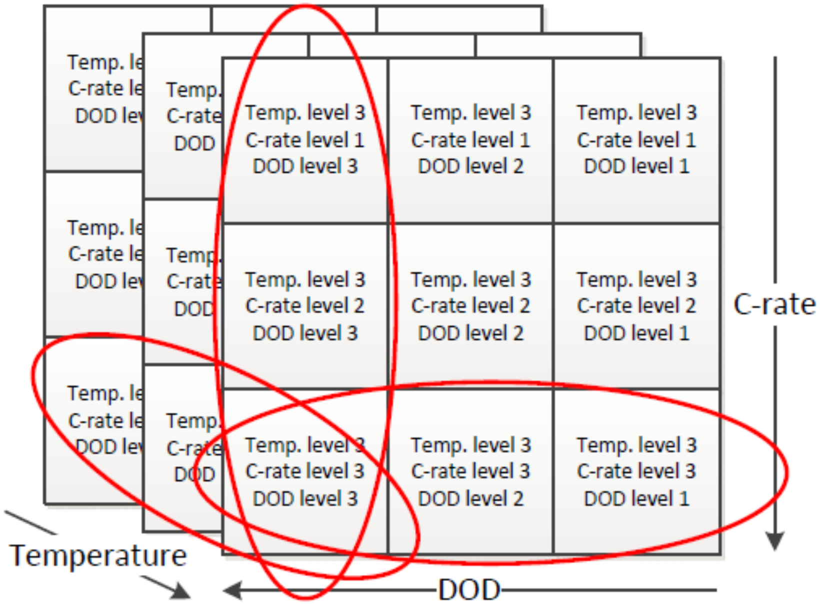
Ageing mechanism	Enhanced by	Result
Growth of SEI, changes of the surface porosity	high DOD, high C-rate	impedance increase
Loss of active surface	high temperature, high SOC	impedance increase
Electrolyte dissolution (oxidation of cathode) and binder dissolution	high temperature, high SOC	impedance increase, capacity loss
Lithium plating	low temperature, high C-rate	impedance increase, capacity loss
Active mass particles loss of contact (mechanical stress because of the changes of volume)	high DOD, high C-rate	capacity loss
Solvent's intercalation, cracking of graphite	over-charging	capacity loss
Conductor corrosion	over-discharge and low SOC	impedance increase

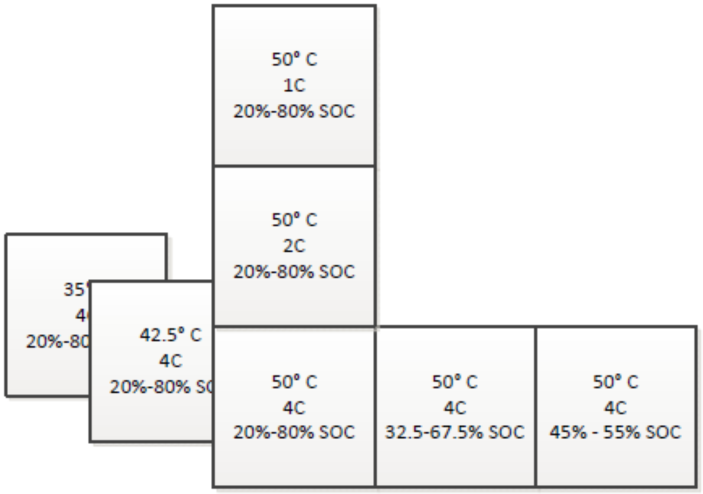
Accelerated calendar lifetime tests (Stage II)



TC	Type of test	Stress levels	Cells denotation	Cell type	Phase length
TC9	Calendar	55°C, SOC=50%	C1, C2, C3	1B	1 month
TC10	Calendar	47.5°C, SOC=50%	C4, C5, C6	1B	1 month
TC11	Calendar	40°C, SOC=50%	C7, C8, C9	1B	1 month

Accelerated cyclling lifetime tests (Stage III)

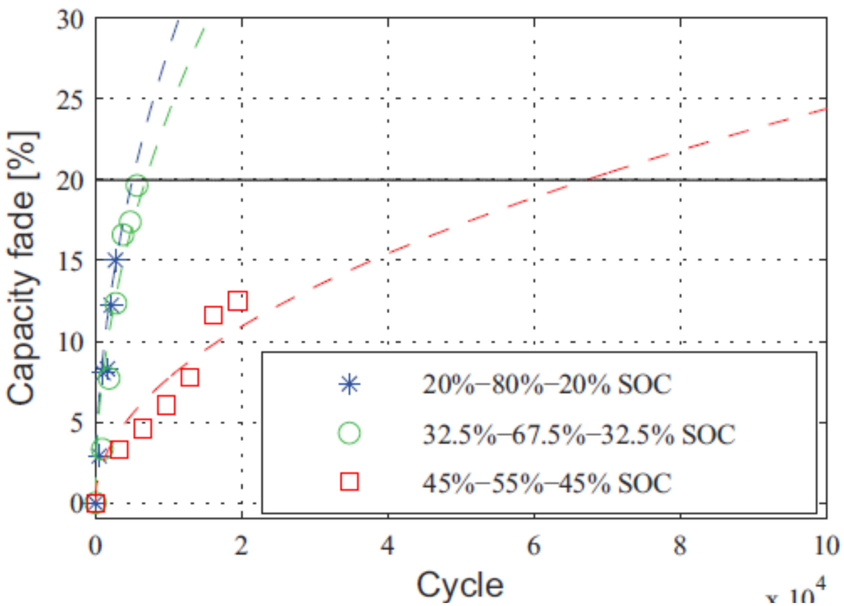


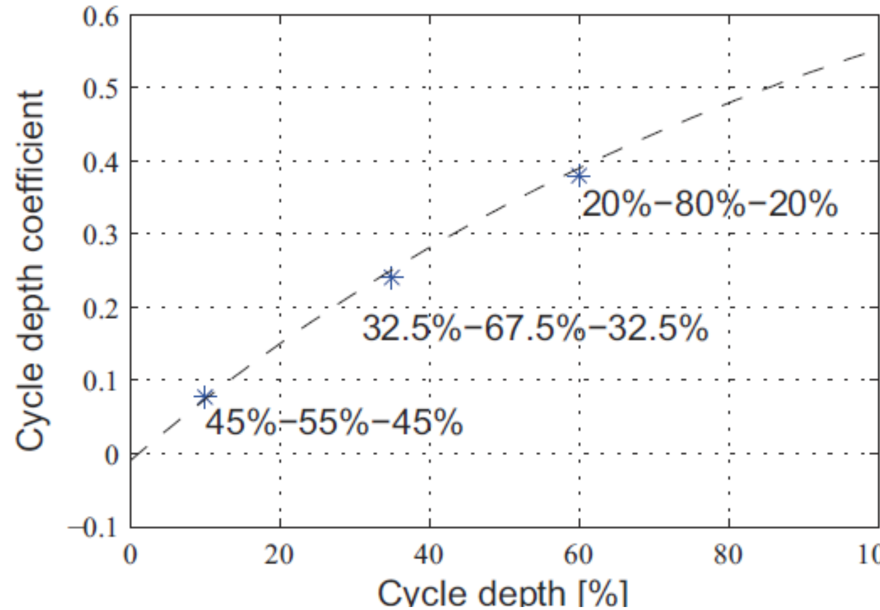


TC	Type of test	Stress levels	Cells denotation	Cell type	Phase length
TC1	Cycling	50°C, 20-80 %DOD, 4C	3.1, 3.2, 3.3	1B	550 cycles
TC2	Cycling	50°C, 32.5-67.5 %DOD, 4C	3.4, 3.5, 3.6	1B	950 cycles
TC3	Cycling	50°C, 45-55 %DOD, 4C	3.7, 3.8, 3.9	1B	3250 cycles
TC4	Cycling	42.5°C, 20-80 %DOD, 4C	3.10, 3.11, 3.12	1B	550 cycles
TC5	Cycling	35°C, 20-80 %DOD, 4C	3.13, 3.14, 3.15	1B	550 cycles
TC6	Cycling	50°C, 20-80 %DOD, 1C	3.16, 3.17	1A	130 cycles
TC7	Cycling	50°C, 20-80 %DOD, 2C	3.18, 3.19	1A	130 cycles
TC8	Cycling	50°C, 20-80 %DOD, 4C	3.20, 3.21	1A	130 cycles

Accelerated cyclling lifetime tests (Stage III)

Influence of the cycle depth on the LFP/C battery cycle ageing





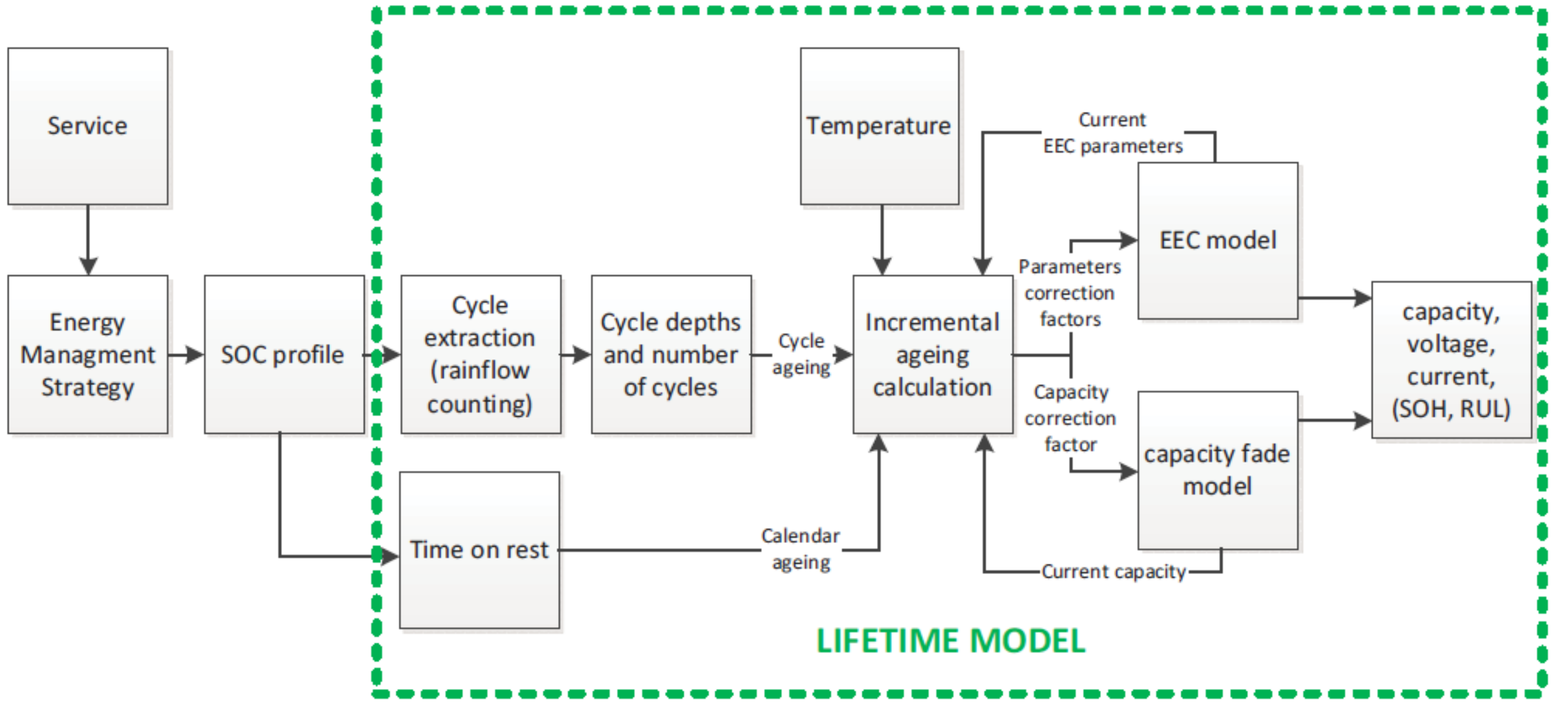
$$C_{T,Cdepth,cycle} = \left[3.0806e^{-5} \cdot exp^{(0.03216 \cdot T)} + 0.7196\right] \cdot \left[-0.9049 \cdot exp^{(-0.00972 \cdot Cdepth + 0.8951)}\right] \cdot cycle^{0.5}$$

$$R_{S_{T,Cdepth,cycle}} = \left(1.8454e^{-10} \cdot exp^{0.06939 \cdot T}\right) \cdot \left(2.381e^{-5} \cdot C_{depth}\right) \cdot cycle$$

$$R_{1_{T,Cdepth,cycle}} = \left(8.9454e^{-13} \cdot exp^{0.08589 \cdot T}\right) \cdot \left(3.282e^{-5} \cdot C_{depth} + 0.0004615\right) \cdot cycle$$

$$R_{2_{T,Cdepth,cycle}} = \left(0.01408 \cdot T - 3.5484\right) \cdot \left(0.0001014 \cdot C_{depth}\right) \cdot cycle$$

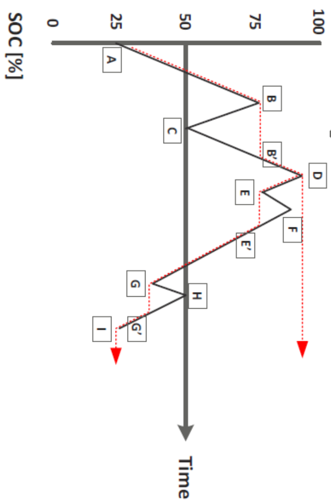
Li-ion battery ageing model



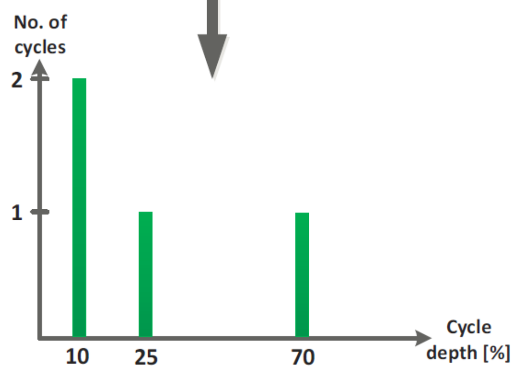
- The lifetime model receives information about the stresses which are coming from the cycle and calendar ageing of the battery;
- The lifetime model performs incremental ageing calculations, accumulates the stresses from the cycling and the calendar ageing, and determines the correction factors for the EEC parameters of the battery and for the capacity correction factor.

Li-ion battery ageing model

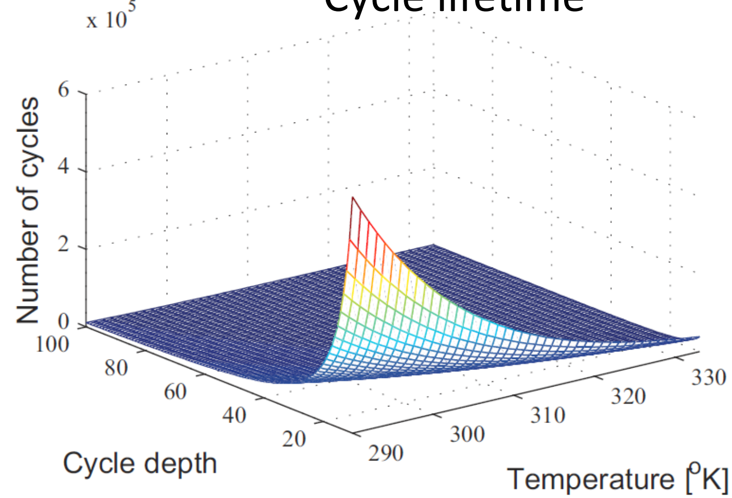
Rainflow cycle counting

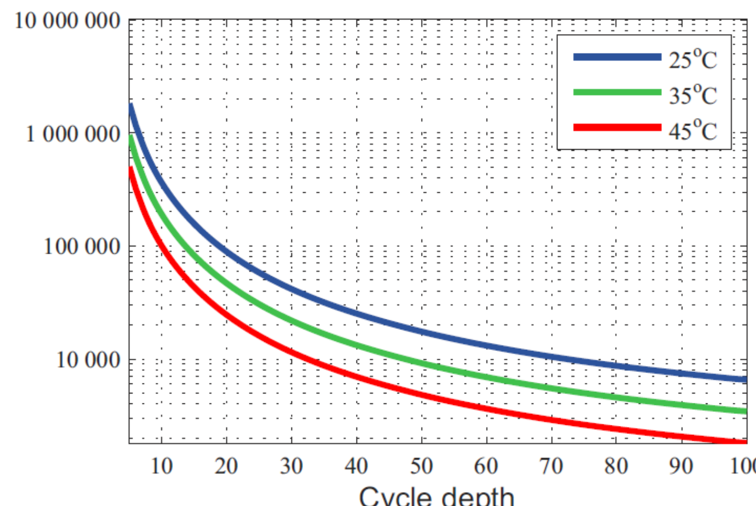


Cycles:	
B-C-B'	Cycle depth=25%
E-F-E'	Cycle depth=10%
G-H-G'	Cycle depth=10%
A-D-I	Cycle depth=70%



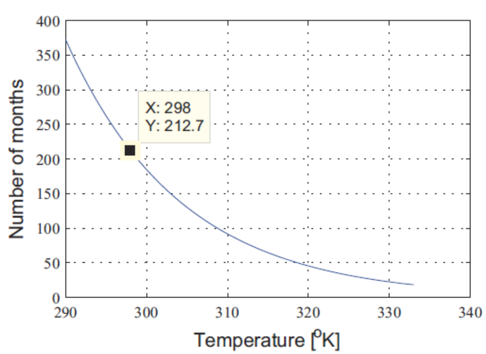
Cycle lifetime





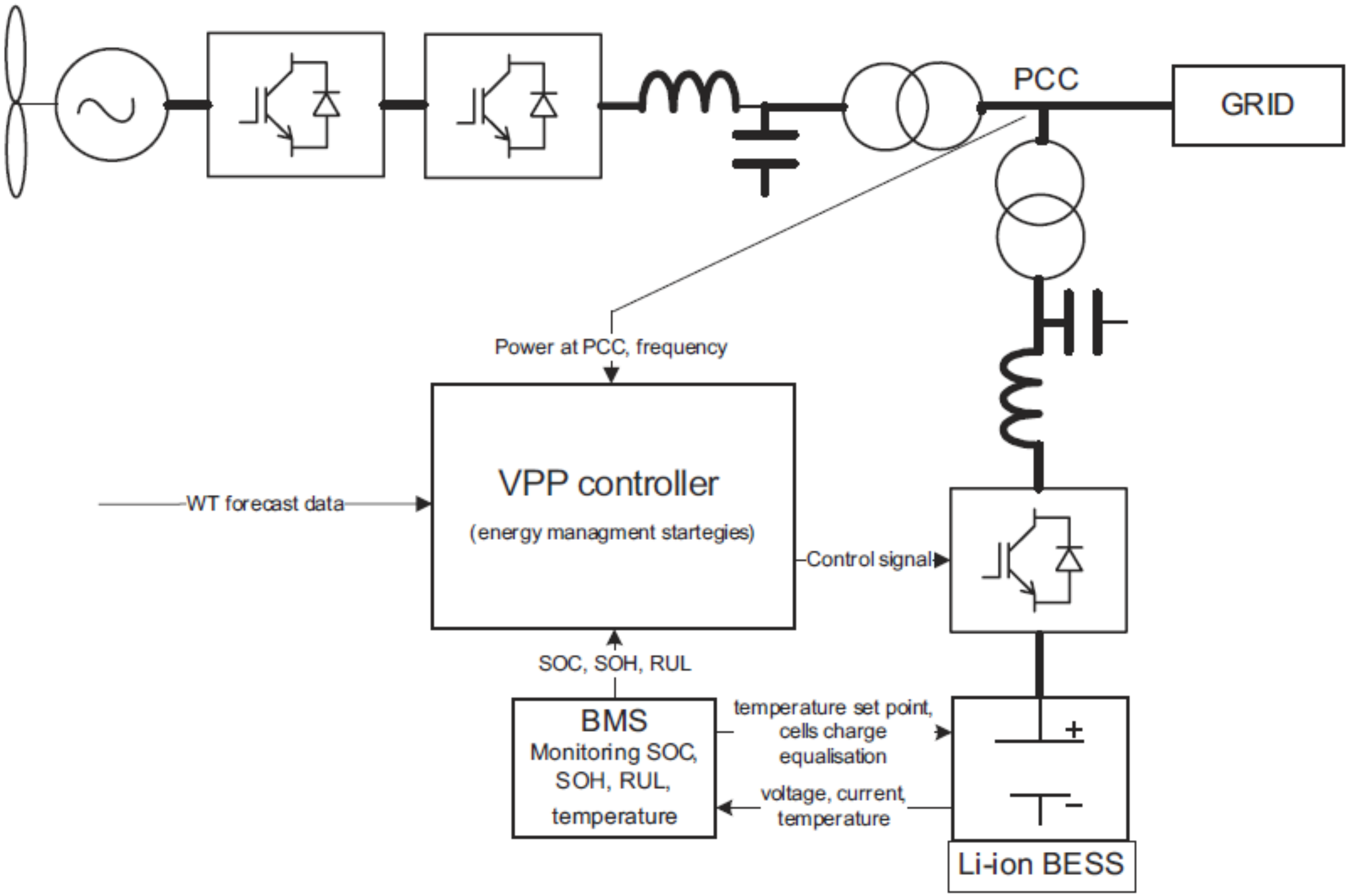
Calendar lifetime

~17,75 years



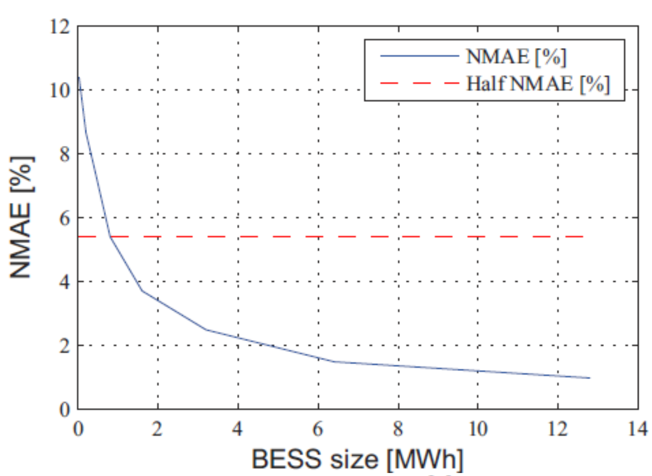
Economical investigations

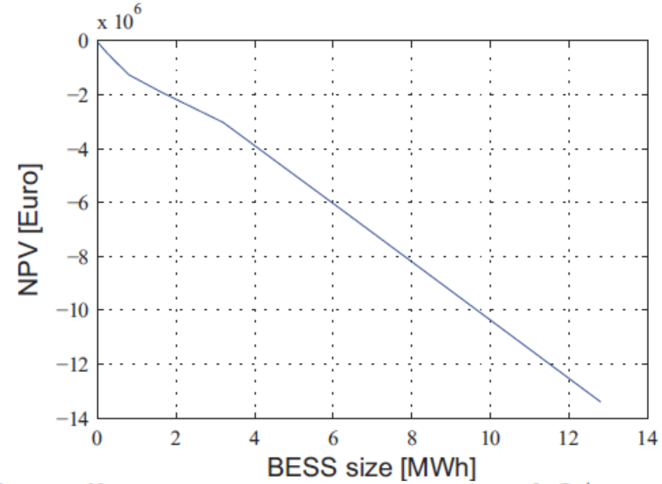
System under study



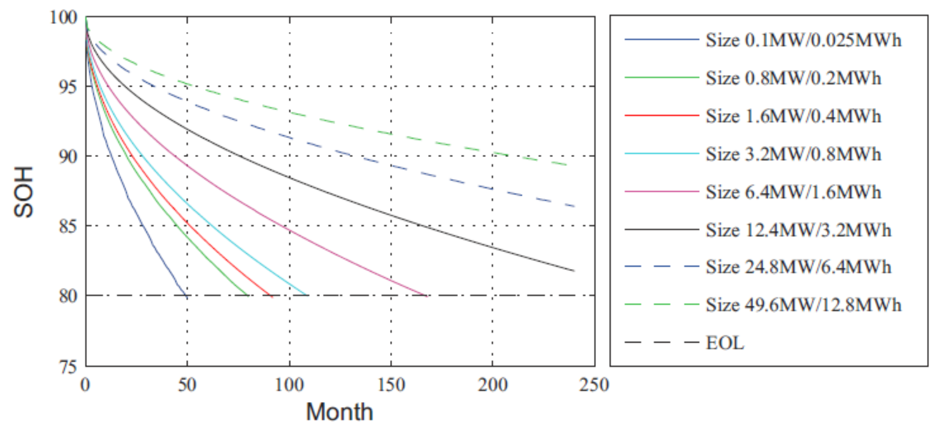
Wind power forecast accuracy improvement service

- **The influence of the Li-ion BESS size on the NMAE and NPV**



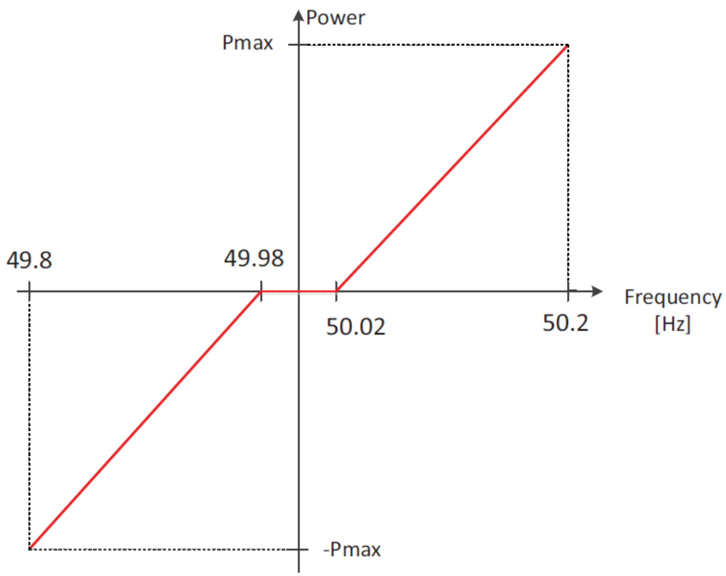


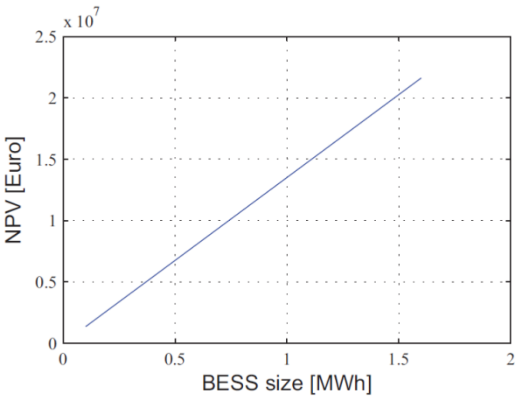
Simulation parameters: storage size (variable), storage round-trip efficiency (90%), storage price (700k€/MWh), power electronics price (100k€/MW), interest rate (5%), SOC interval <*0% ; 100%*>.

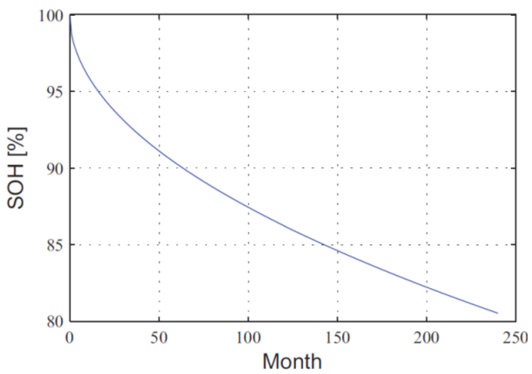


Primary frequency regulation

- Li-ion BESS is providing PFR service with a droop
- Market prices for PFR for West Denmark for the year 2010
- Elbas (upward and downward) balancing market prices for West Denmark for the year 2010
- Assumption: all bids are won (all 6 blocks per day)







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Lifetime predictions – system level

Slides are not publically available because of the non-disclosure agreement between Maciej Swierczynski and Vestas A/S

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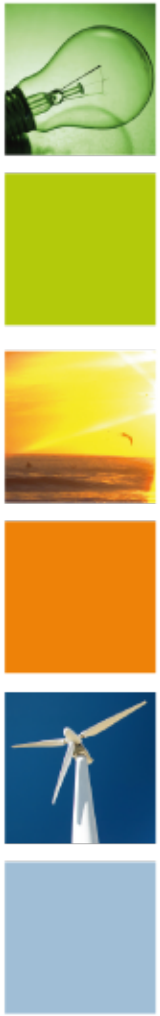

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Conclusions

- The grid codes for the future WPPs will be more stringent on the electricity markets with the high wind power penetration. The future WTs will need to have a generation characteristics, which are similar or the same as the CGUs in order to be interconnected into the grid. Moreover, it is expected that the large WPPs will be in the future replacing the CGUs and they will need to take the responsibility for the grid and provide the more predictable power;
- $LiFePO_4$/C and $LMO_2/Li_4Ti_5O_{12}$ chemistries are very promising for the integration with the VPP (long lifetime at partial DOD (especially low cycle cost), low self-discharge, high-efficiency, low O&M costs and safety);
- Accurate lifetime models are very important for the battery sizing, energy management strategy and for the development of the accurate business model
- The lifetime for the considered Li-ion battery cell strongly depends on the battery temperature and the cycle depth;
- Calendar ageing dependence on the temperature is following closely the Arrhenius equation while for the cycle ageing the Arrhenius relationship does not hold;
- For the considered services, the focus capacity fade is the most important degradation process, which has the highest influence on the revenues from the services; thus SOH should be related with the capacity fade for the both considered services;
- The developed lifetime model is based on the incremental ageing calculation and it is able to predict the battery SOH, RUL at different battery cell ages;
- Proposed benchmark allows for studying different Li-ion BESS sizes, parameters, SOC operation intervals, energy management strategies and their influence on the Li-ion BESS lifetime and investment NPV. It can be used as a tool for sizing the BESS for a specific service and determination of the optimal BESS energy management strategy, which assures the highest NPVs;
- At present on the Danish market the wind power forecast accuracy improvement service is not profitable with the Li-ion BESS, while the PFR service with the Li-ion BESS is very profitable

Industrial PhD course in Storage Systems based on Li+ion Batteries for Stationary Applications

15-17 October 2013

Remus Teodorescu
Professor
Aalborg University

Dirk Uwe Sauer
Professor
(RWTH Aachen)

Pedro Rodriguez
Professor
(Abengoa Research)

Maciej Swierczynski
Postdoc Fellow
Aalborg University

Course Program

Day 1: Tuesday May 1st, 2012

08:30	Course Registration
09:00	Overview of Electrochemical Battery Technologies
10:00	Coffee Break
10:30	Overview of Stationary Applications
12:00	Lunch
13:00	Applications to PV Plants and to WP plants
14:30	Coffee Break
15:00	Matlab Exercise for Optima l Sizing of Stor age in Different Applications

Day 2: Wednesday May 2nd, 2012

08:30	Principles of Electrochemistry – Part I
10:00	Coffee Break
10:30	Principles of Electrochemistry – Part II
12:00	Lunch
13:00	Li-Ion Batteries, Technology, Performance, Ageing Mechanism and Modeling – Part I
14:30	Coffee Break
15:00	Li-Ion Batteries, Technology, Performance, Ageing Mechanism and Modeling – Part II

Day 3, Thursday May 3rd, 2012

08:30	Life Time Modeling
10:00	Coffee Break
10:30	Impedance-based Modeling
12:00	Lunch
13:00	Matlab Exercise on Curve Fitting and Param eter Extraction
14:30	Coffee Break
15:00	Lab visit
15:30	End of Course

Thank you for your attention!

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