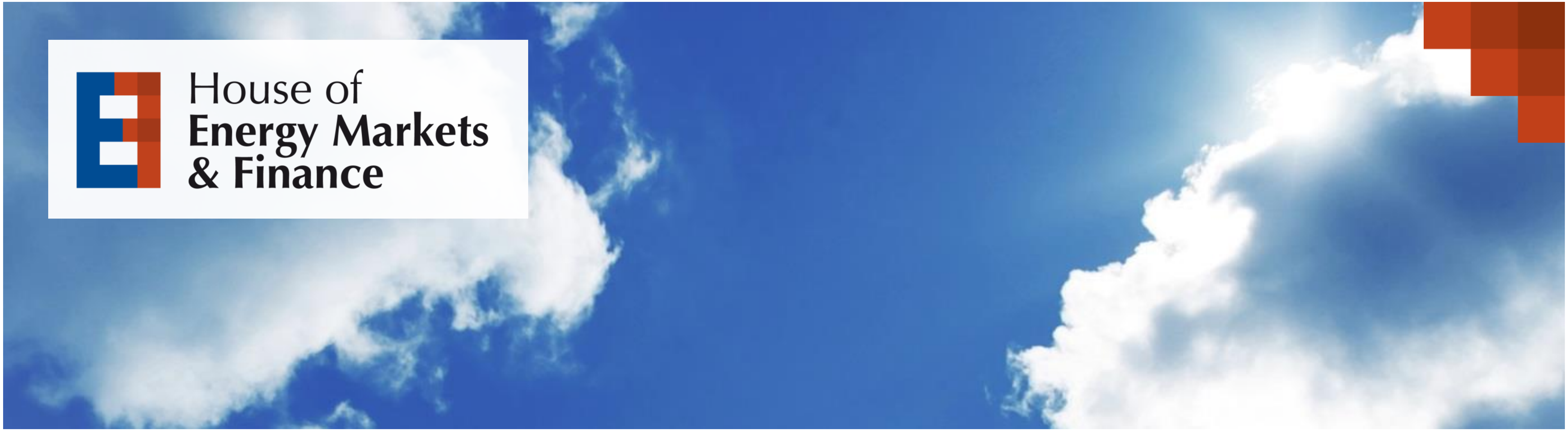

Battery aging and their implications for efficient operation and valuation

Strommarkttreffen | 25. August | Flexibilität | Berlin / Germanwatch

Benjamin Böcker

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Future energy systems:

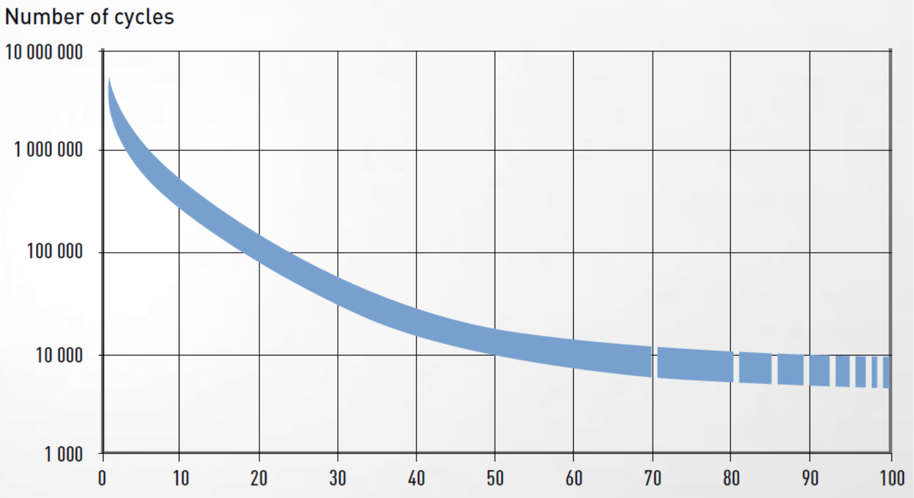
- more and more dominated by renewable resources (primary supply-dependent like wind and PV)
- increasing need of flexibilities

Battery technologies as one promising flexibility option

- strong competition with other storage as well as conventional technologies
- the actual operation causes aging, which has a significant effect on expected lifetime
- appropriate valuation need an adjusted approach taking aging into account, either
  - optimizing whole lifetime (not known beforehand) – typically several years or
  - optimizing a certain period (day, week, month, year) considering corresponding lifetime

Simplified battery aging model, considering

- cyclical (see figure) as well as
- calendrical aging



Quelle: Saft, 2014

Robust optimization model, to

- valuate battery technologies for a specific application (e.g. spot & reserve market, private households),
- considering battery aging as well as the corresponding lifetime
- for a representative price curve/pattern (e.g. one week, month or year)
- derive of optimal control decisions

Basic assumptions

Battery aging model

- battery age:

$$a(t) = a_0 + \sum_{t \in T} da(t)$$

- aging:

$$da(t) = da_{cal}(t) + da_{cyc}^{+}(t) + da_{cyc}^{-}(t)$$

- normalized capacity

$$v(t) = 1 - (1 - v_e)a(t)$$

Parameter/Variable	Unit	Description
t	$[h]$	time
T	$[h]$	Optimization time
Δt	$[h]$	time-step
$s(t)$	$[-]$	State of charge (energy)
$s^{+}(t)$	$[-]$	Battery charging (power), $\frac{\Delta s(t)}{\Delta t}$ $with\ \Delta s(t) > 0$
$s^{-}(t)$	$[-]$	Battery discharging (power), $-\frac{\Delta s(t)}{\Delta t}$ $with\ \Delta s(t) < 0$
$v(t)$	$[-]$	Normalized capacity (energy)
$dv_{cal}(t)$	$[-]$	Loss of v through calendrical aging
$a(t)$	$[-]$	Battery age (0 to 1)
$da_{cal}(t)$	$[-]$	Battery aging – calendrical
$da_{cyc}^{+}(t), da_{cyc}^{-}(t)$	$[-]$	Battery aging – cyclical while $s^{+}(t)$ or $s^{-}(t)$
α_1, α_2	$[h^{-1}]$	Aging parameter – calendrical
α_3	$[-]$	Aging parameter – calendrical
β_1, β_2	$[-]$	Aging parameter – cyclical
v_e	$[-]$	Normalized capacity $v(t)$ at end of life

Calendrical Aging (Lithium ion) – Database

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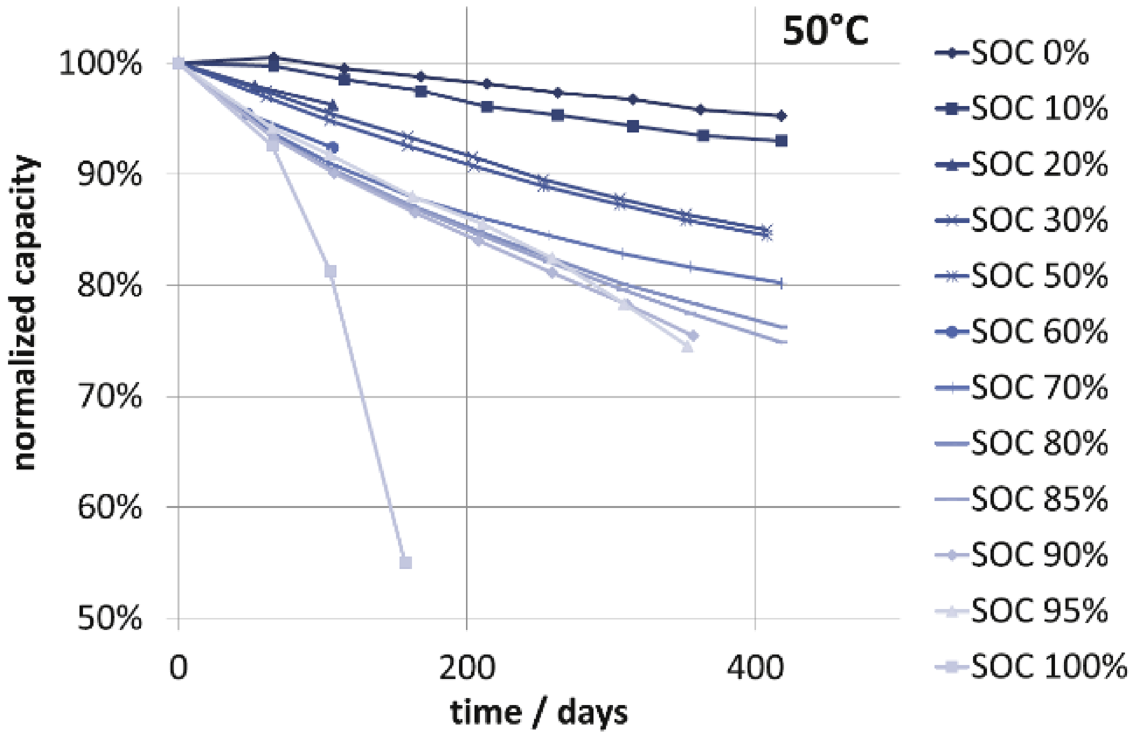
Battery aging model

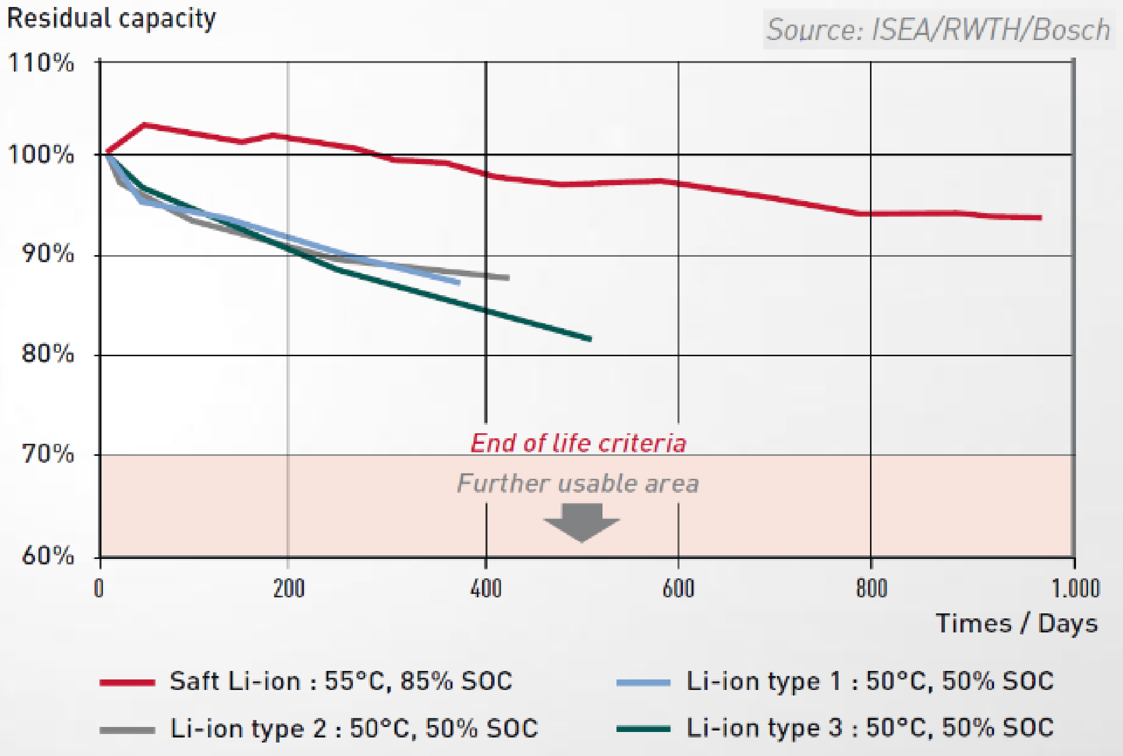
1 2 3 4 5

Normalized capacity vs. time



Quelle: Ecker, Nieto, Käbitz, Schmalstieg, Blanke, Warnecke, Sauer; Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithiumion batteries; Journal of Power Sources, 2013

Calendar life time (one year calendar life time at 50°C corresponds to approximately 5.6 years at 25°C)



Quelle: Saft, 2014

Calendrical Aging (Lithium ion) – Model Approach

Battery aging model

- Summary: Aging increases with higher $s(t)$ (State of charge, SOC)
- Combined Model:
  1. Relation to $s(t)$ at 50°C

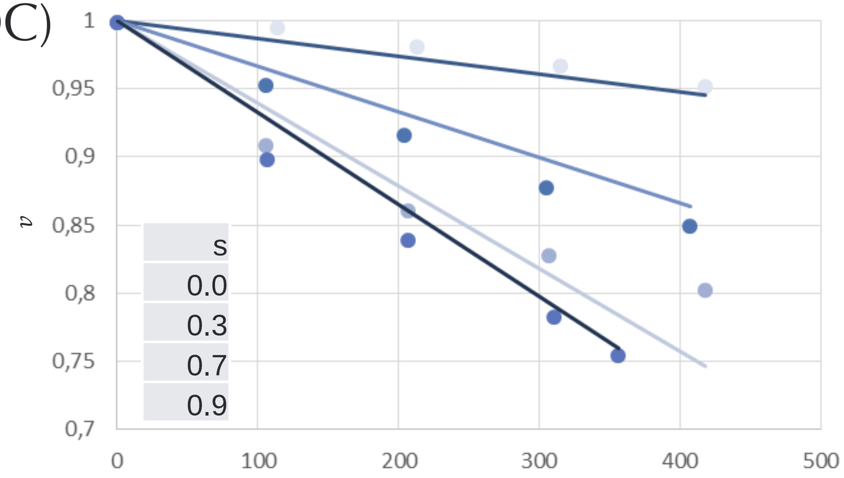
$$dv_{cal}(t) = -(\alpha_1 s(t) + \alpha_2)dt$$

  2. Adjustment to SAFT Data and
     Saft: ~10% Aging in 20 years (25°C)

$$da_{cal}(t) = (\alpha_1 s(t) + \alpha_2)\frac{\alpha_3}{(1-v_e)}dt$$

  3. In discrete time

$$da_{cal}(t) = \left(\alpha_1\left(s(t) + 0.5\left(s^+(t) - s^-(t)\right)\Delta t\right) + \alpha_2\right)\frac{\alpha_3 \Delta t}{(1-v_e)}$$



α_1	6.804E-04	$[h^{-1}]$
α_2	1.306E-04	$[h^{-1}]$
α_3	1.064E-03	$[-]$

Calendrical Aging (Lithium ion) – Illustration

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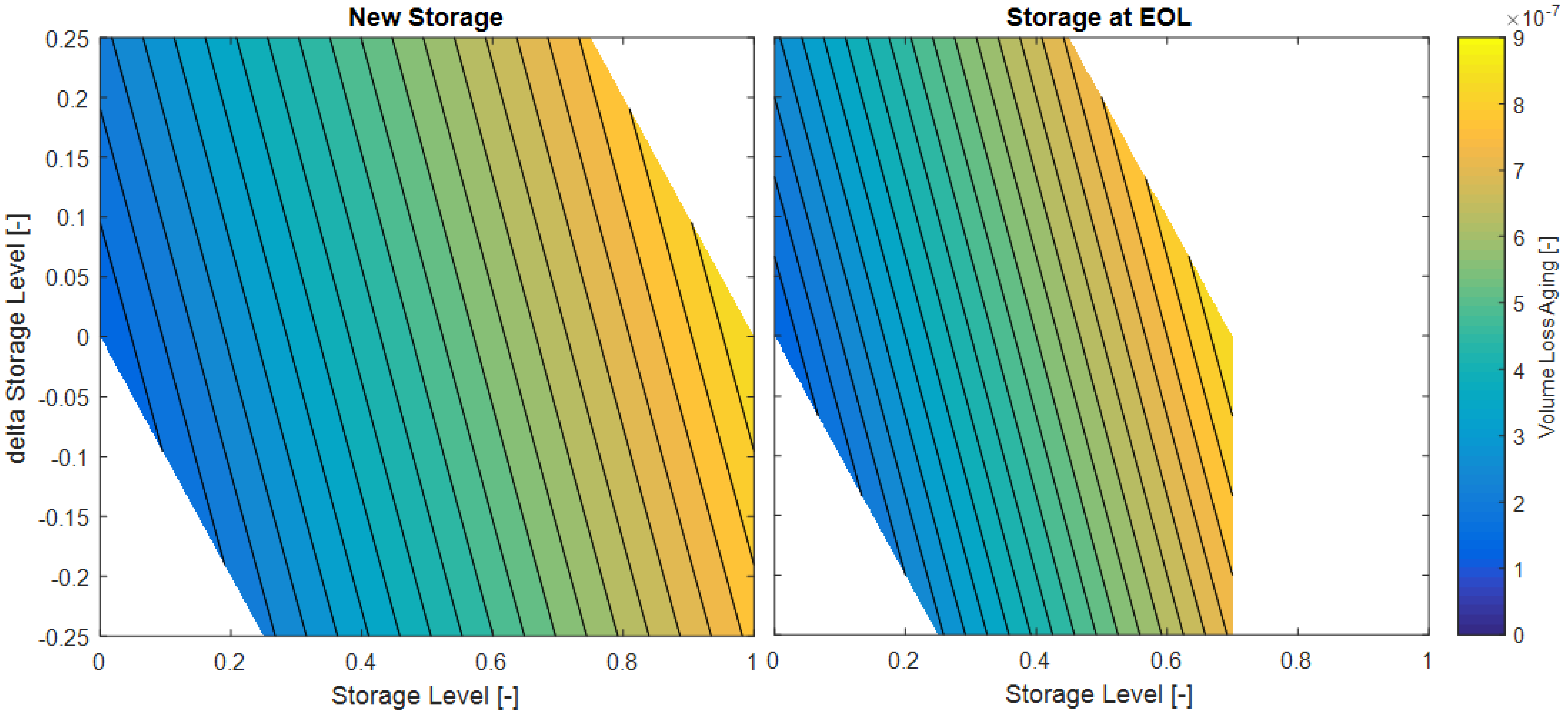
Battery aging model

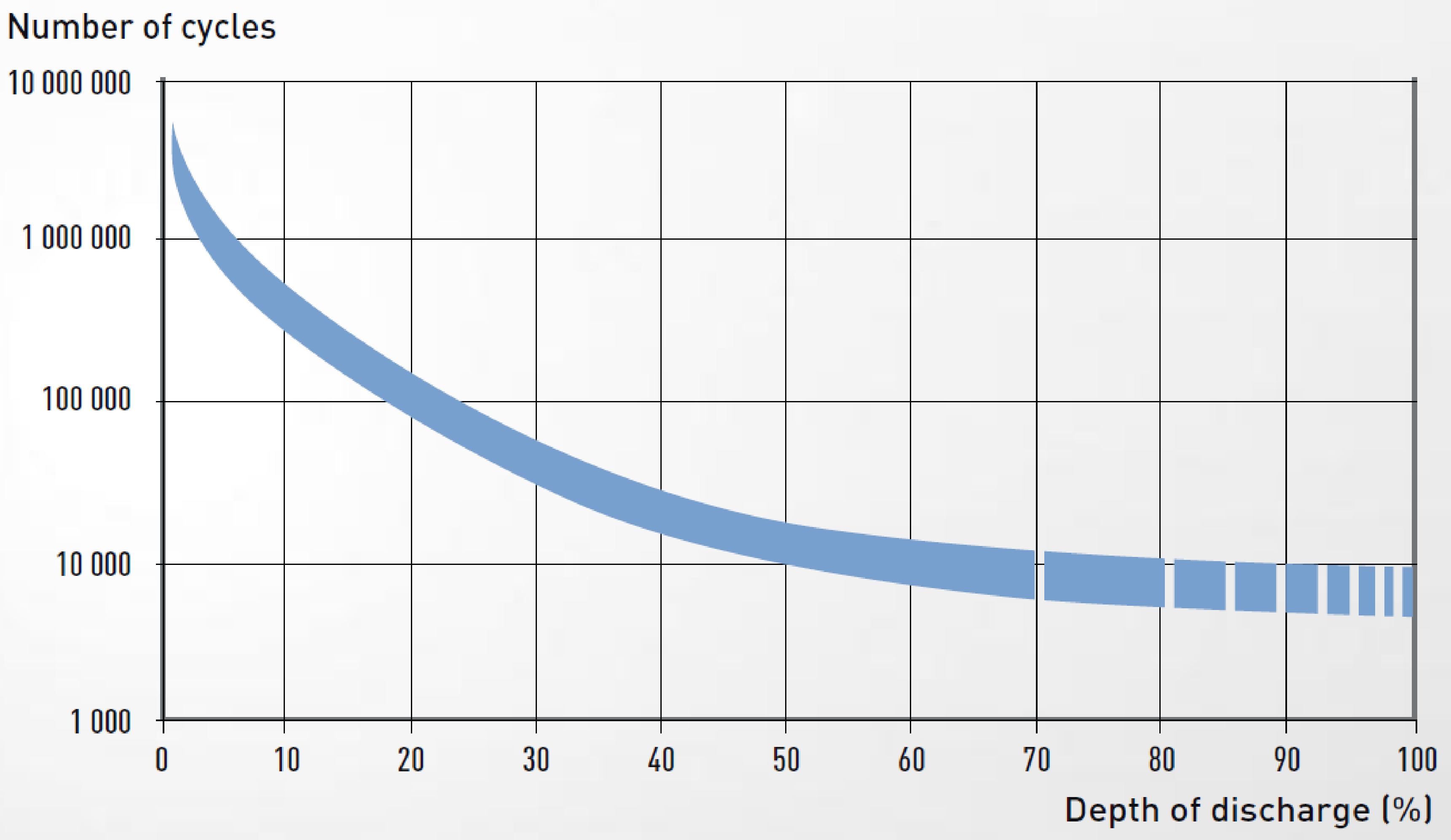
1 2 3 4 5



House of Energy Markets & Finance

Cyclical Aging (Lithium ion) – Database

Battery aging model



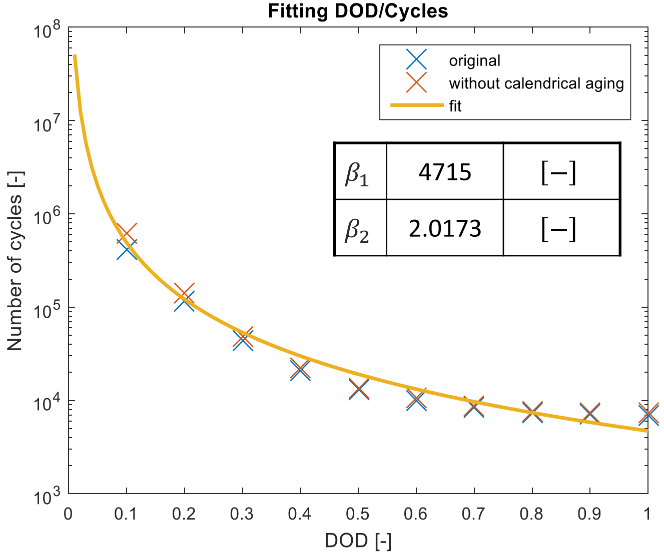
Quelle: Saft, 2014

Cyclical Aging (Lithium ion) – Model Approach

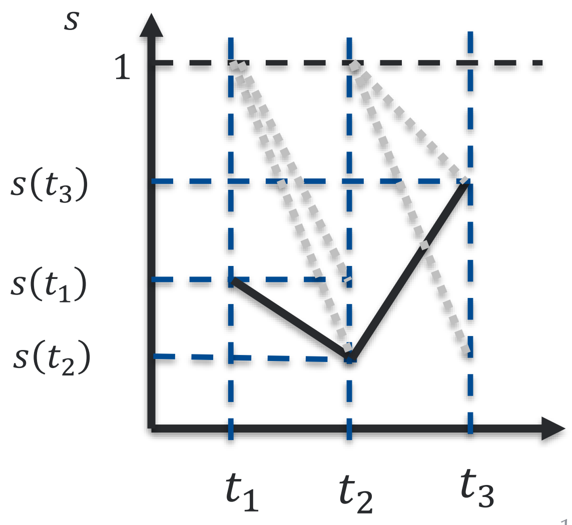
- Summary: Aging increases with higher depth of discharge (DOD)
- Basic dependency (Number of cycles for different DOD)

$$N(DOD) = \beta_1 \cdot DOD^{-\beta_2} \qquad \frac{da_{cyc}}{DOD} = \frac{1}{N(DOD)} = \frac{1}{\beta_1} \cdot DOD^{\beta_2}$$

- Integrative approach, aging while charging and discharging
  - charging: $$da_{cyc}^{+}(t) = \frac{1}{2\beta_1} \cdot \left(\left(1 - s(t)\right)^{\beta_2} - \left(1 - s(t) - s^{+}(t)\Delta t\right)^{\beta_2} \right)$$
  - discharging: $$da_{cyc}^{-}(t) = \frac{1}{2\beta_1} \cdot \left(\left(1 - s(t) + s^{-}(t)\Delta t\right)^{\beta_2} - \left(1 - s(t)\right)^{\beta_2} \right)$$

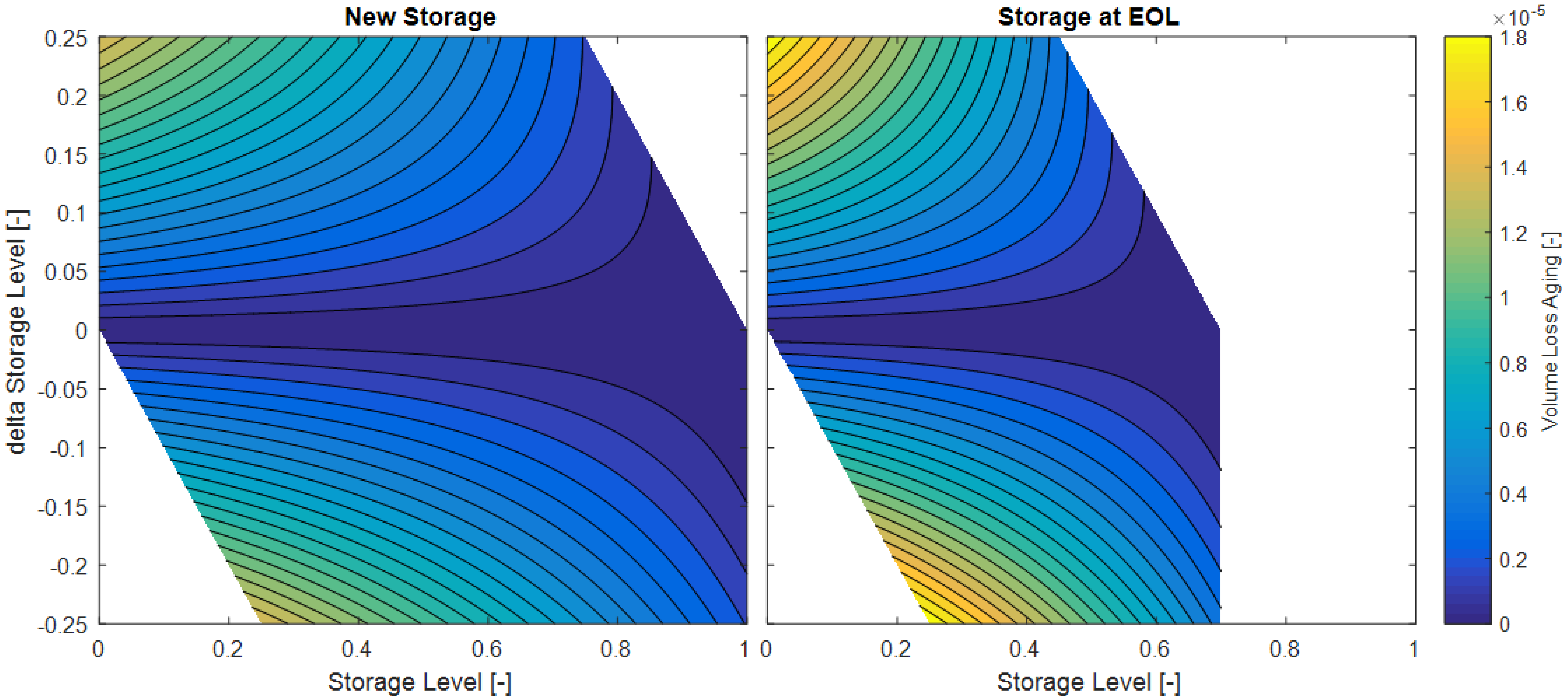


β_1	4715	[−]
β_2	2.0173	[−]



Cyclical Aging (Lithium ion) – Illustration

Battery aging model



Optimization Problem: Objective Function

Implications for storage valuation – analytics

Par.	Unit	Description
N	$[-]$	Number of Periods
η	$[-]$	Storage charging and discharging efficiency
V_S	$[MWh]$	Storage Volume
K_S	$[MW]$	Storage Power
i_T	$[-]$	Interest Rate for Period T
g	$[-]$	Revenue Changing Rate for Period T

Objective function

$$\max\left(M_R \sum_{t \in T} R_{sm}(t)\right)$$

- Revenues spot market (initial)

$$R_{sm}(t) = \left(\eta s^{-}(t) - \frac{1}{\eta} s^{+}(t)\right) \Delta t \cdot V_S \cdot p_{sm}(t)$$

- Revenue multiplier $M_R = f(a_0, a(t), i_T)$ as adjusted NPV for
  - linear decreasing annuity (revenues) due to available storage volume
  - increasing revenues due to changes in the price pattern (driven by more RES or competitors) – optional
  - resulting lifetime (given by aging and optimization time period)

Optimization Problem: Revenue Multiplier

Implications for storage valuation – analytics

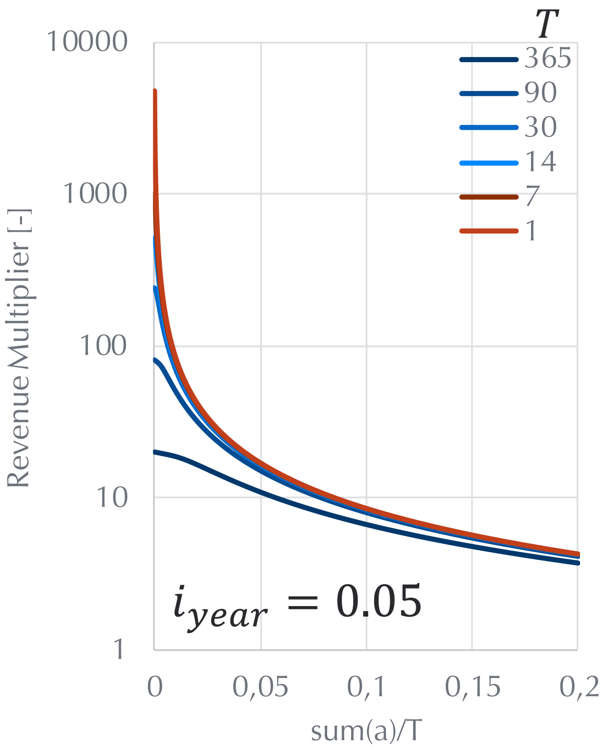
- Revenue Multiplier

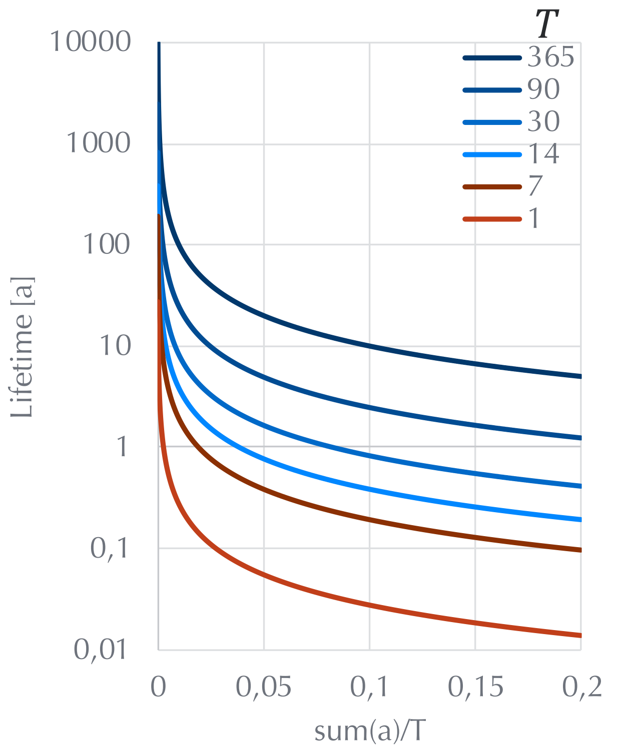
$$M_R = \frac{(R_0 - m_R)q_T - R_0 + (m_R(N+1) - R_0){q_T}^{-N+1} + (R_0 - m_R N){q_T}^{-N}}{(q_T - 1)^2}$$

  - $N = \frac{1-a_0}{\sum_{t\in T} da(t)}$, $\quad q_T = \frac{1+i_T}{1+g}$, $\quad m_R = \frac{(1-v_e)(1-a_0)}{N}$,
  - $R_0 = v_e + (1-a_0)(1-v_e) + \frac{1}{2} m_R$

- Extension of classic present value of annuity

$$M_R = R_0 \frac{1-q^{-N}}{q-1}$$





Optimization Problem: Restrictions

Implications for storage valuation – analytics

1 2 3 4 5

- State of charge (storage level)

$$s(t+1) = s(t) + \big(s^+(t) - s^-(t)\big)\Delta t$$
$$s(1) = s(T) + \big(s^+(T) - s^-(T)\big)\Delta t$$
$$s(t) \leq 1$$

- Power restriction

$$s^+(t) + s^-(t) \leq \frac{K_S}{V_S}$$

- Aging

$$da(t) = da_{cal}(t) + da_{cyc}^+(t) + da_{cyc}^-(t)$$

  - calendrical

$$da_{cal}(t) = \Big(\alpha_1\big(s(t) + 0.5\big(s^+(t) - s^-(t)\big)\Delta t\big) + \alpha_2\Big)\frac{\alpha_3 \Delta t}{(1 - v_e)}$$

  - cyclical

$$da_{cyc}^+(t) = \frac{1}{2\beta_1} \cdot \Big(\big(1 - s(t)\big)^{\beta_2} - \big(1 - s(t) - s^+(t)\Delta t\big)^{\beta_2}\Big) \qquad da_{cyc}^-(t) = \frac{1}{2\beta_1} \cdot \Big(\big(1 - s(t) + s^-(t)\Delta t\big)^{\beta_2} - \big(1 - s(t)\big)^{\beta_2}\Big)$$

Agenda

Application Data

Base Case

- Lithium ion Battery (cf. left table)
- Investigation year – 2016,
  hourly resolution (mean: 29.0 €/MWh, std: 14.0 €/MWh)

Sensitivities

- no consideration of aging effects in operational optimization
- different optimization time periods (one year or weeks)
- 2016, quarter hourly resolution
  (mean: 29.0 €/MWh, std: 15.4 €/MWh)
- 2030, hourly resolution (mean: 48.1 €/MWh, std: 21.5 €/MWh)

	Unit	Value
V_S	$[MWh]$	1
K_S	$[MW]$	1
η^*	$[-]$	0.9
i_{year}	$[-]$	0.05
$\boldsymbol{g}$	$[-]$	0
$\boldsymbol{a}_0$	$[-]$	0
v_e	$[-]$	0.7
α_1	$[h^{-1}]$	6.8e-4
α_2	$[h^{-1}]$	1.3e-4
α_3	$[-]$	1.1e-3
β_1	$[-]$	5000
β_2	$[-]$	2

$*$ for charging and discharging, 0.81 roundtrip efficiency

Base Case – General results

Application | 1 | 2 | 3 | 4 | 5

Considering aging

- increases the value of the battery by 74%, while
- decreases first year spot revenues by 36%
- increasing the corresponding lifetime with factors 2.4

Value of the battery system as target costs

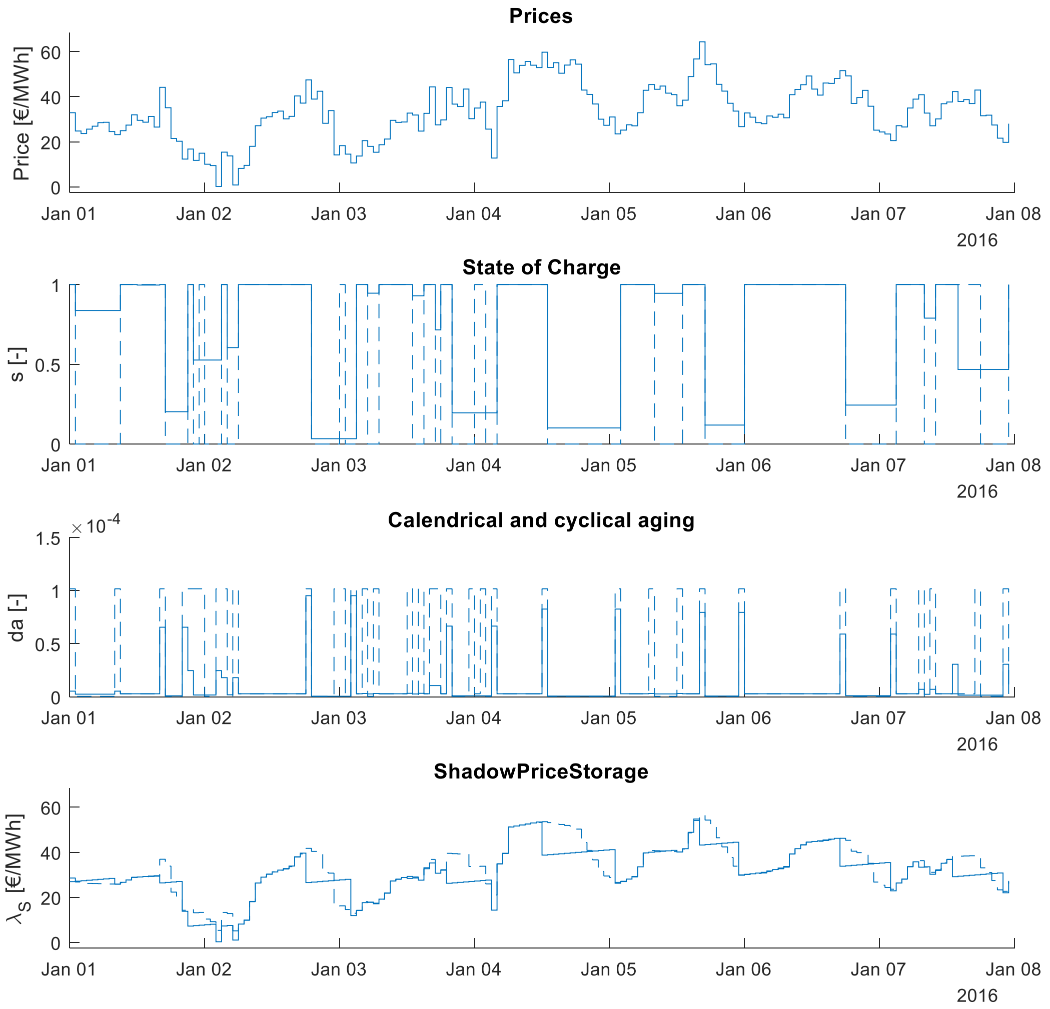
- 45 €/kWh/kW respectively 76 €/kWh/kW, already volume-based costs are significantly higher (>>100€/kWh)
- as expected inefficient investment in a lithium ion battery system (application, arbitrage hourly spot-market, 2016)

2016 ($T = 8760h$, $\Delta t = 1h$)	Hourly	
	~~aging~~	aging
Battery Value [k€]	44.9	76.0
Aging [-]	0.214	0.063
Lifetime [Yrs]	4.7	16.0
Rev. Spot [€]	12,652.4	8,145.8
Rev. Mply. [-]	3.5	9.4

Base Case – Storage operation

- no consideration of aging effects
  - bang-bang strategy ~18 full cycles
  - maximizing current profit

- consideration of aging effects
  - depth of discharging depends on prices
  - avoid high depth of discharge, only 7 cycles below 0.5
  - trade off between generating revenues and expected lifetime

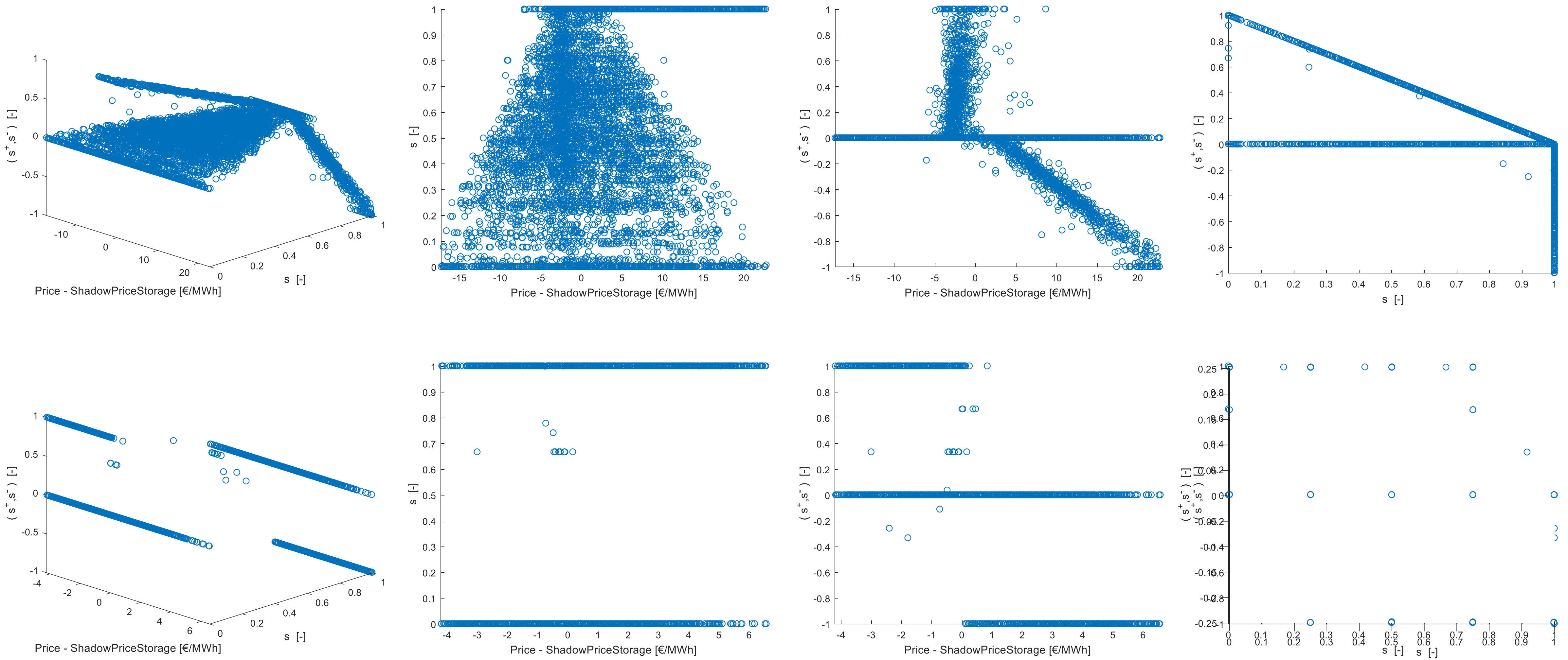


Base Case – Optimal decision – delta shadow price of storage content

Application

With aging

Without aging

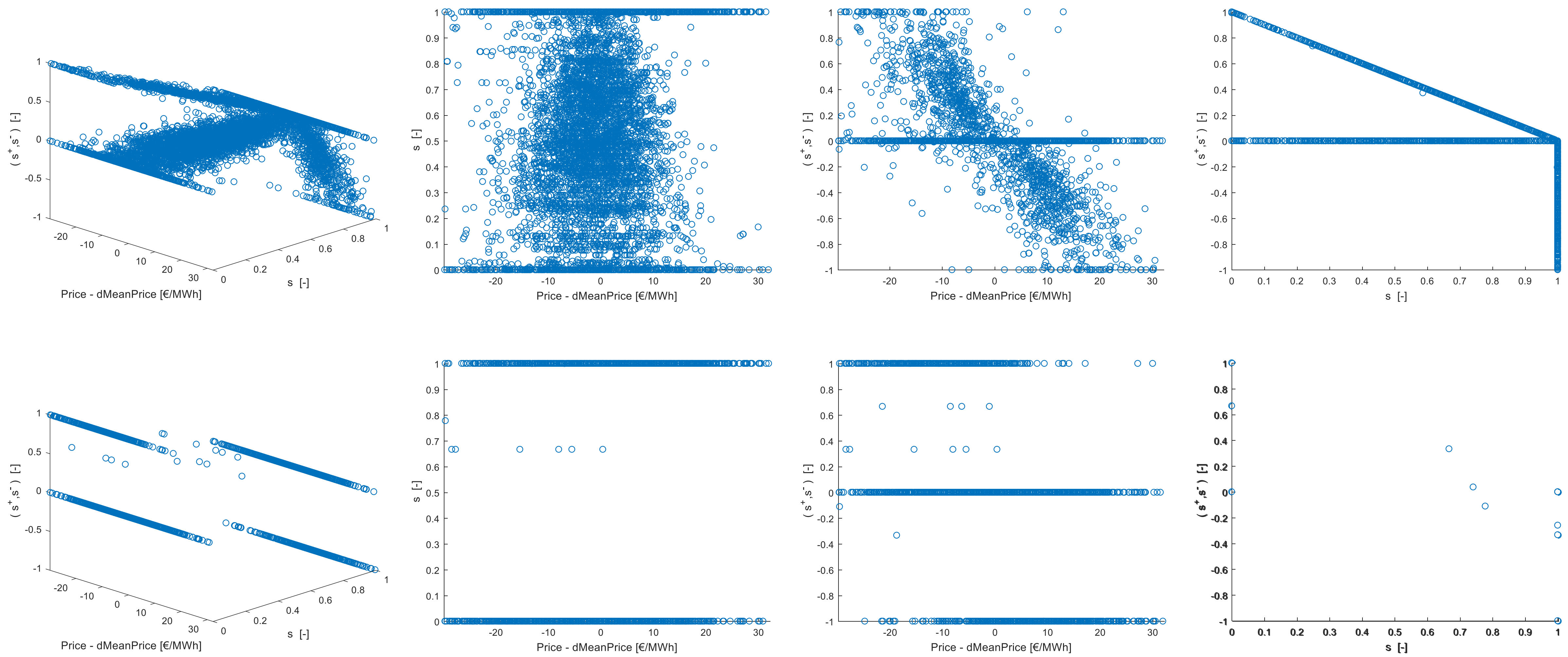


Base Case – Optimal decision – delta daily mean

Application

With aging

Without aging



Results – Sensitivities (not finished)

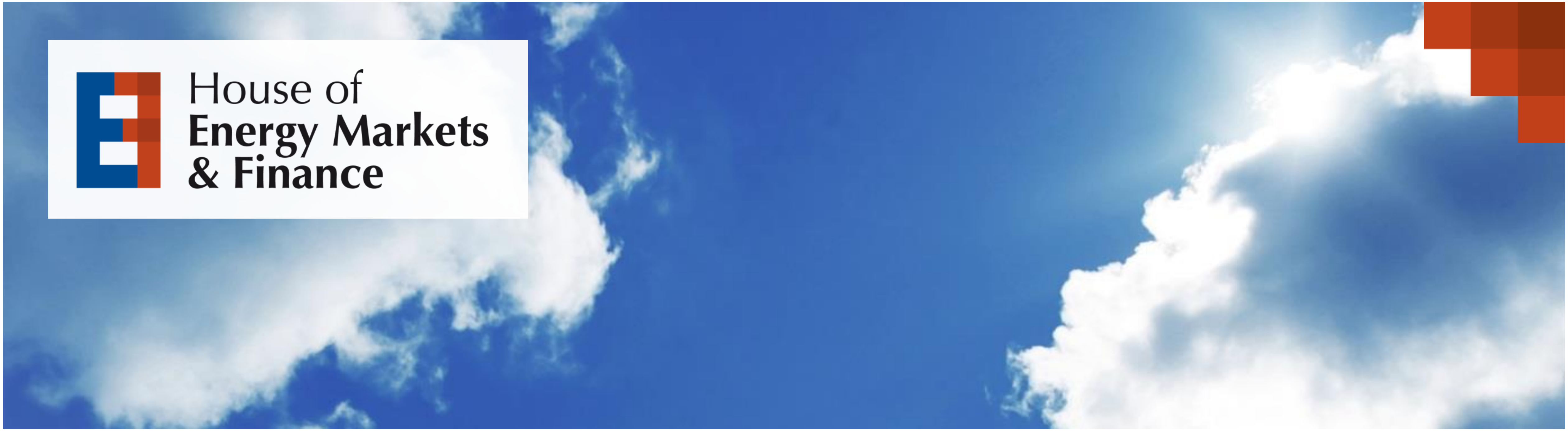
$[-, yr, T\ [d], \Delta t\ [h]]$	Hourly, 2016, 365,1		Hourly, 2030, 365,1		qHourly, 2016, 365,1		Hourly, 2016, 7,1*		qHourly, 2016, 7,1*	
	~~aging~~	aging	~~aging~~	aging	~~aging~~	aging	~~aging~~	aging	~~aging~~	aging
Storage Value [k€]	44.0	76.6	70.7	126.3			45.5 [12.6]	73.0 [28.3]	47.1 [11.9]	128.4 [44.7]
Aging [-]	0.214	0.063	0.209	0.064						
Lifetime [Yrs]	4.7	16.0	4.8	15.7			5.0 [1.3]	14.8 [2.3]	2.1 [0.3]	14.1 [4.2]
Rev. Spot [€]	12652.4	8145.8	19810.1	13561.5						
Rev. Mply. [-]	3.5	9.4	3.6	9.3						

not finished

$[-, yr, T\ [d], \Delta t\ [h]]$	Hourly, 2016, 365,1		Hourly, 2030, 365,1		qHourly, 2016, 365,1		Hourly, 2016, 7,1*		qHourly, 2016, 7,1*	
	~~aging~~	aging	~~aging~~	aging	~~aging~~	aging	~~aging~~	aging	~~aging~~	aging
d Storage Value [-]			60,4%	64,9%			3,4%	-4,7%	6,9%	67,6%
d Aging [-]			-2,7%	1,4%						
d Lifetime [-]			2,7%	-1,4%			6,9%	-7,2%	-54,3%	-11,8%
d Rev. Spot [-]			56,6%	66,5%						
d Rev. Mply. [-]			2,5%	-1,0%						

not finished

- Considering battery aging significantly improve valuation
- Simplified battery aging model also usable for other applications
- Robust algorithm (but non-linear) due to convexity (missing analytical prove)
- Further sensitivities / next steps
  - Second-Life Application (two stage aging process, e.g. double aging after EOL), additional value
  - g (increasing revenues) variations (driven by 2016 and 2030 results)
  - comparison to alternative aging implementations
  - Different aging points (decision only relative)
  - Derivation of representative price pattern (?)



Many Thanks

Böcker, B.: Battery aging and their implications for efficient operation and valuation, mimeo, 2017.

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Sensitivity quarter hourly spot market – Storage operation

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