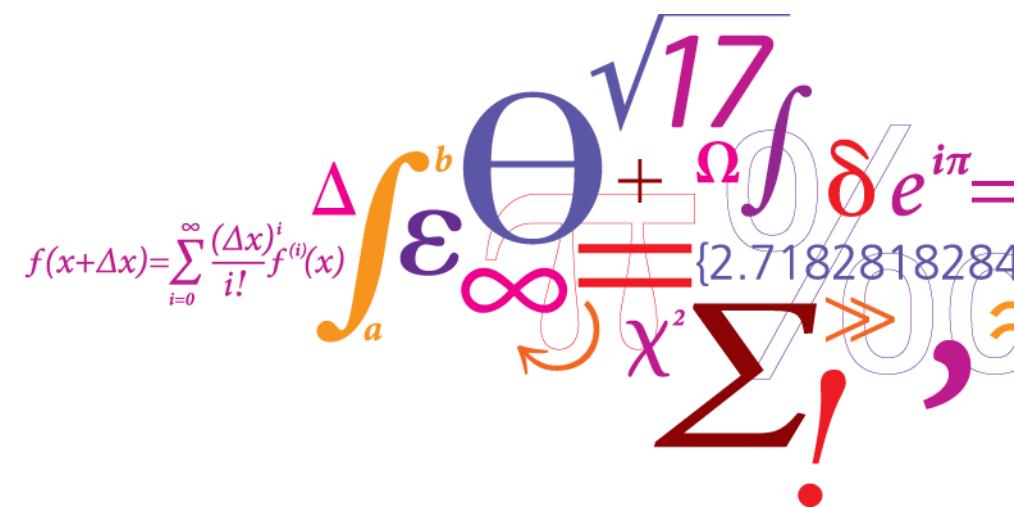


# Controlling the frequency – scheduling and degradation

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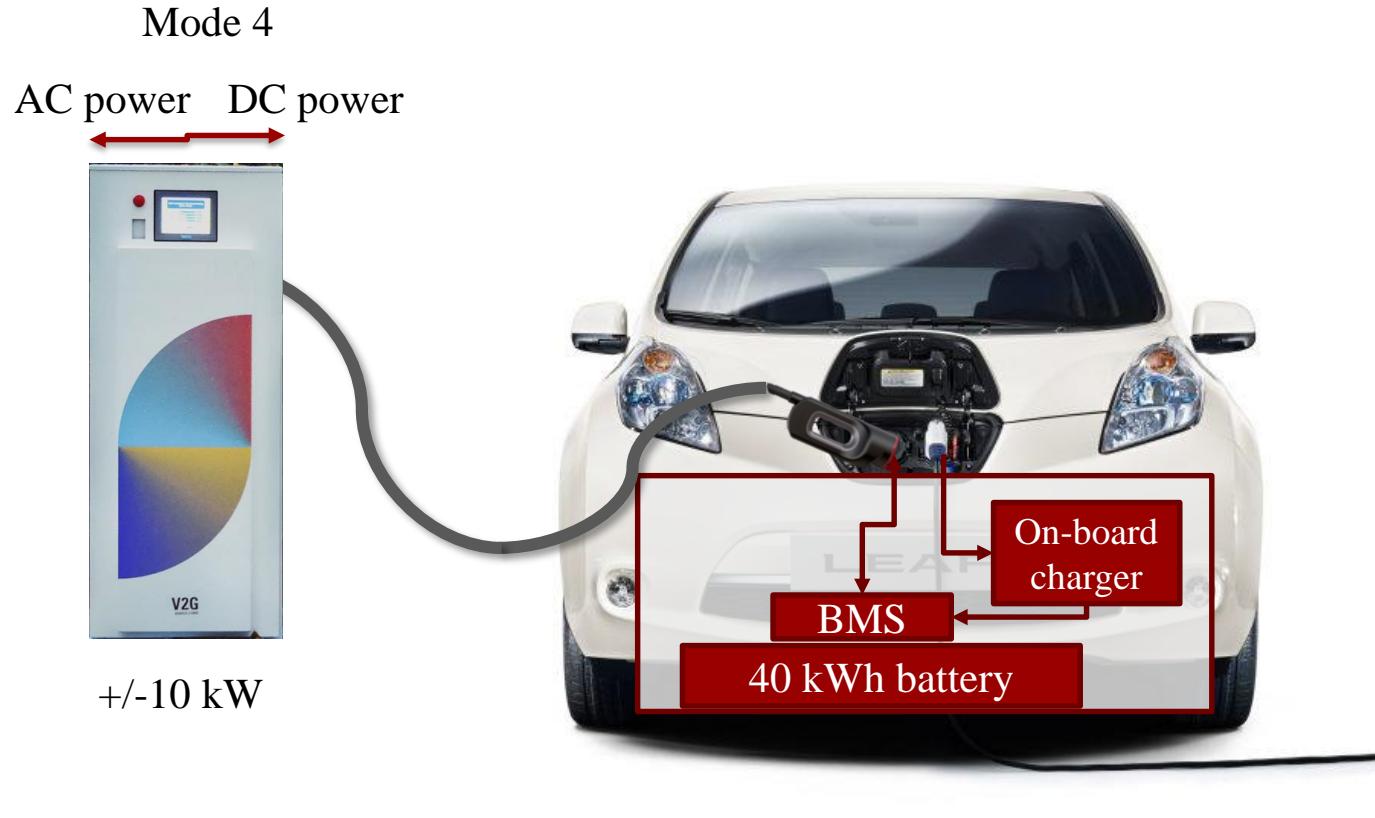
Technical University of Denmark  
*Center for Electric Power and Energy,*  
*Frederiksborgvej 399, 4000 Roskilde, Denmark*

$$f(x+\Delta x) = \sum_{i=0}^{\infty} \frac{(\Delta x)^i}{i!} f^{(i)}(x)$$


# Outline

- Frequency regulation with electric vehicles
- Battery degradation modelling
- The energy content of the frequency
- Optimal scheduling
- Economic revenue

# AC and DC charging options for EVs

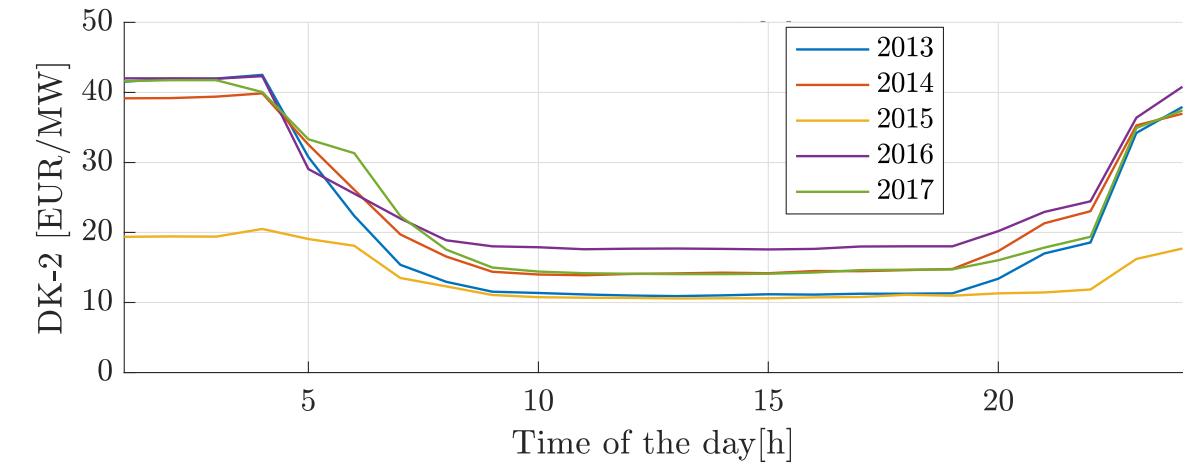
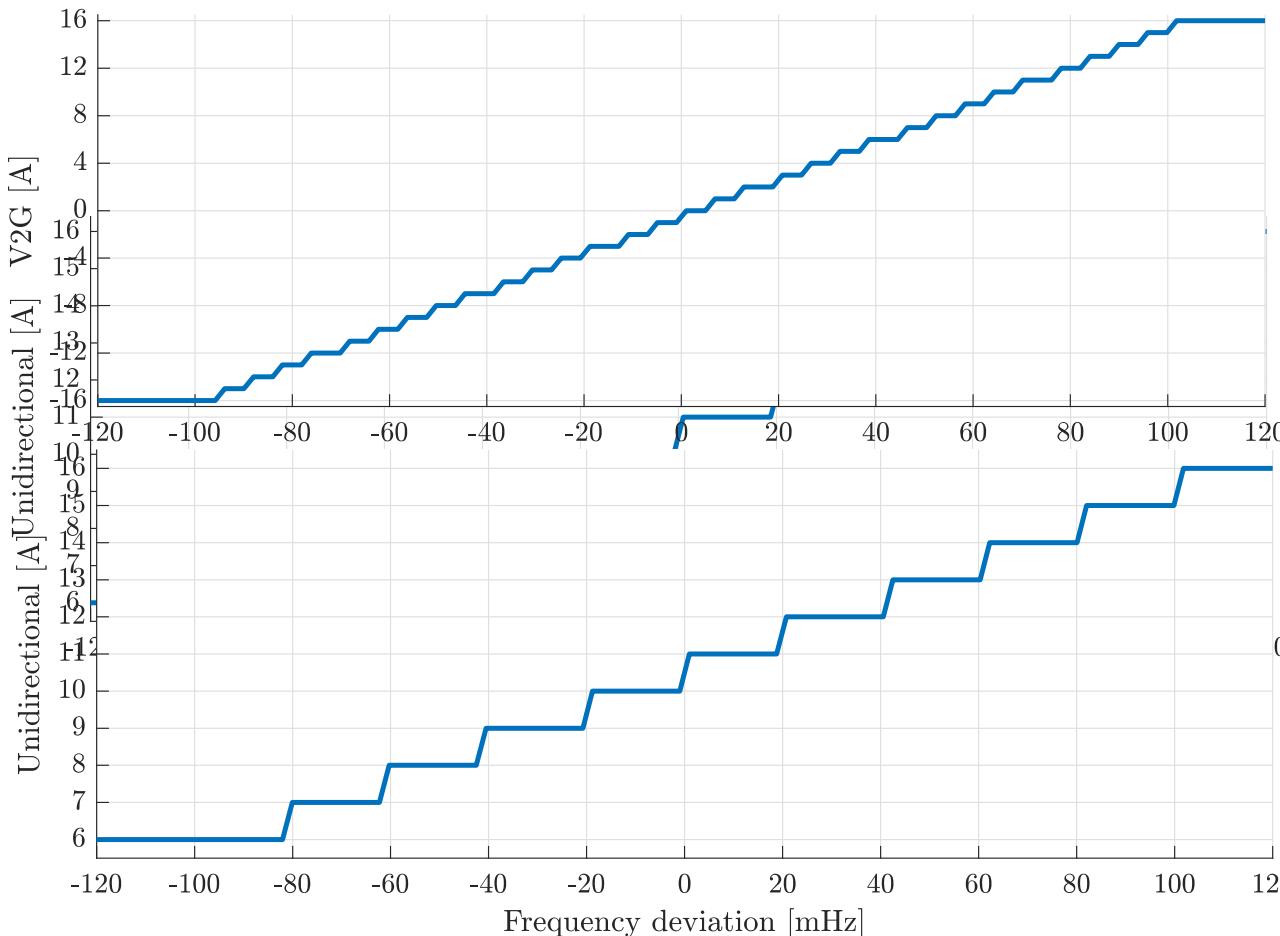


Mode 3

3.7-7.4 kW - 1  
phase

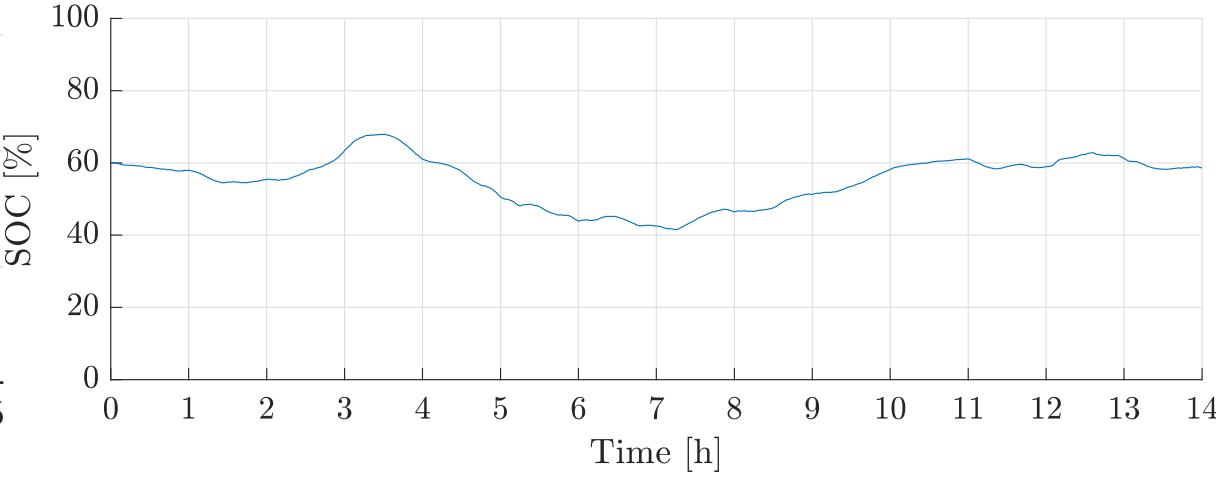
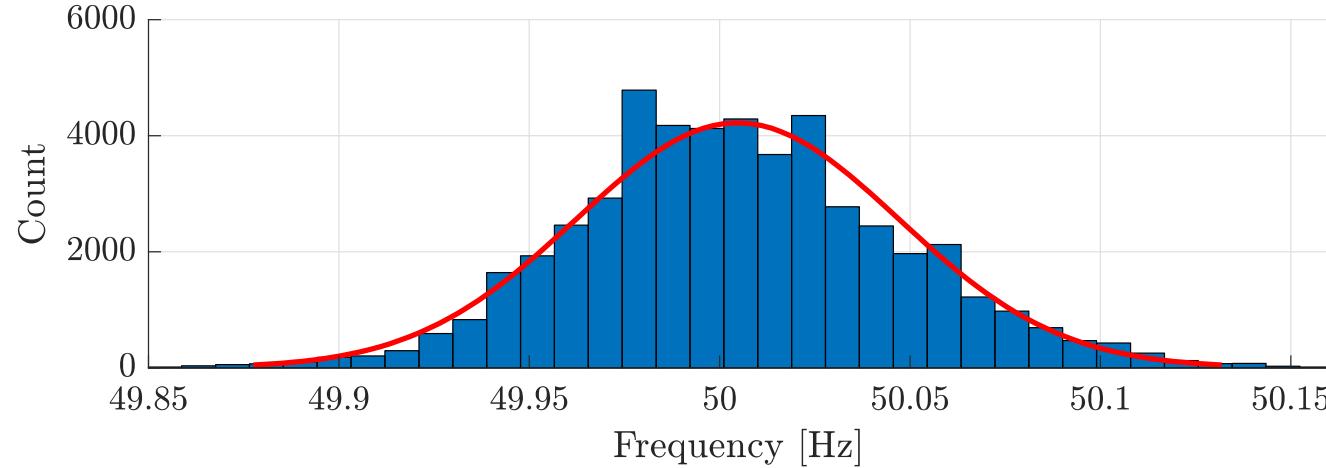
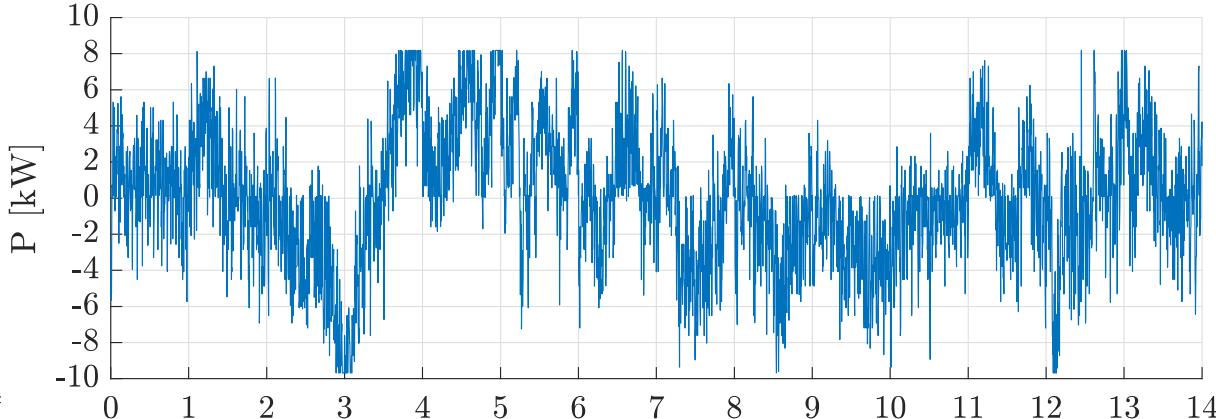
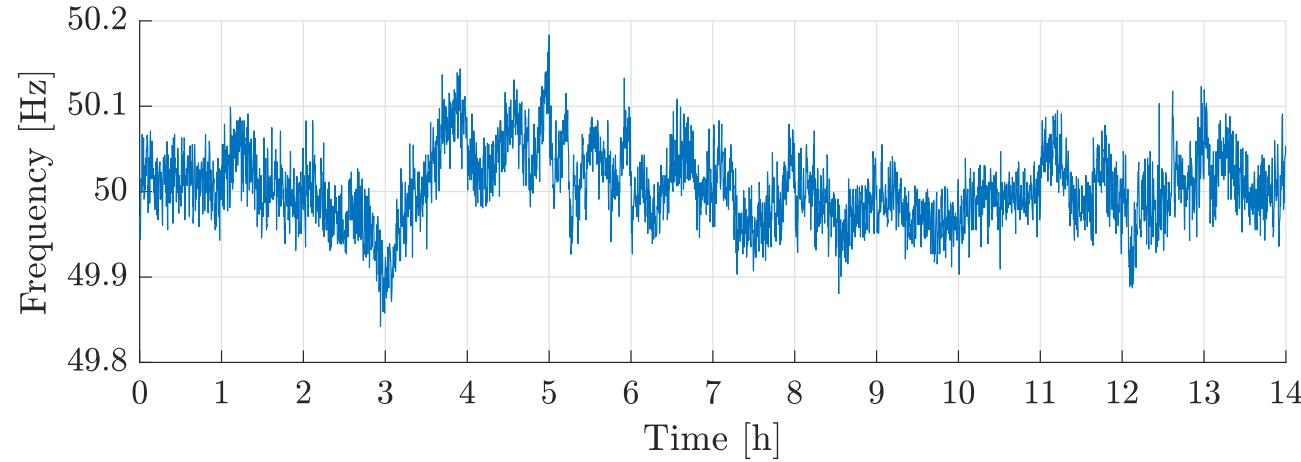


# Primary Frequency Control – Earnings



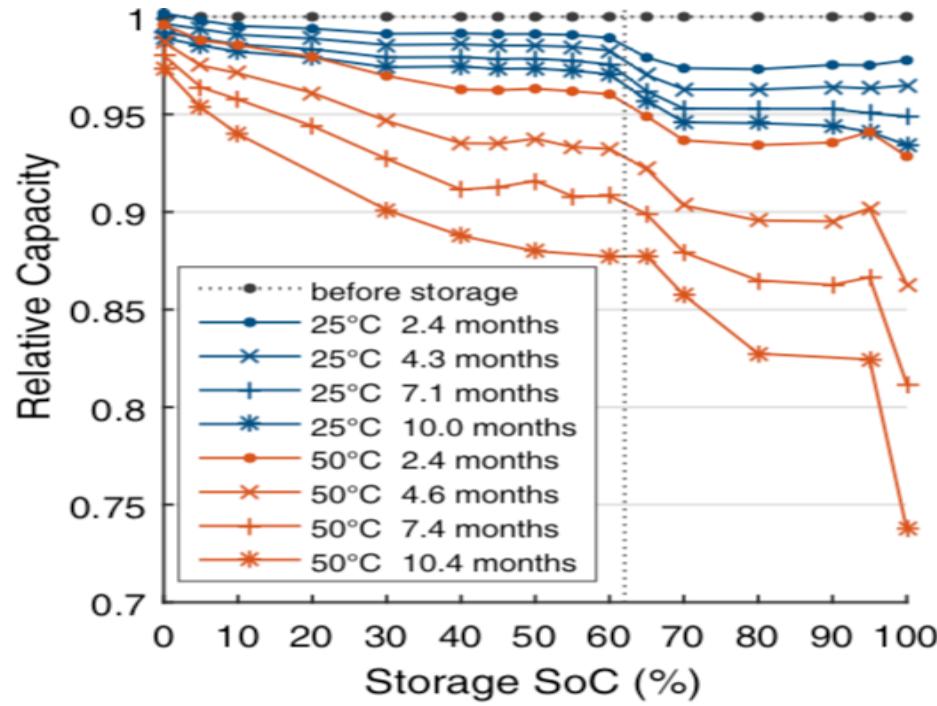
A. Thingvad, S. Martinenas, P. B. Andersen, M. Marinelli, O. J. Olesen and B. E. Christensen, “Economic Comparison of Electric Vehicles Performing Unidirectional and Bidirectional Frequency Control in Denmark with Practical Validation” in IEEE UPEC, Coimbra, 2016.

# Frequency sample – 12<sup>th</sup> Sep. 17:00 to 13<sup>th</sup> Sep 07:00

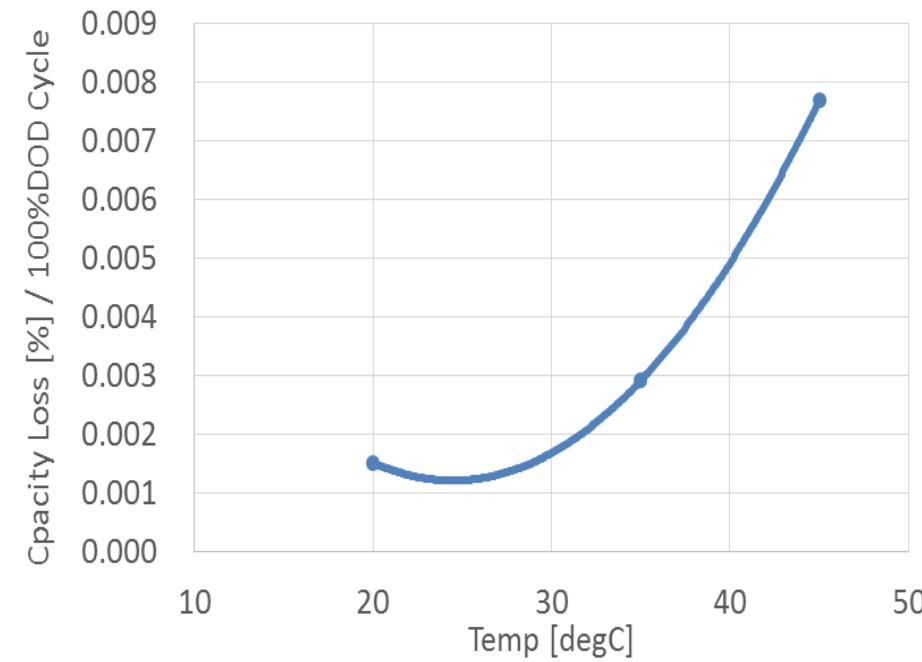




# Calendar aging and cycle degradation

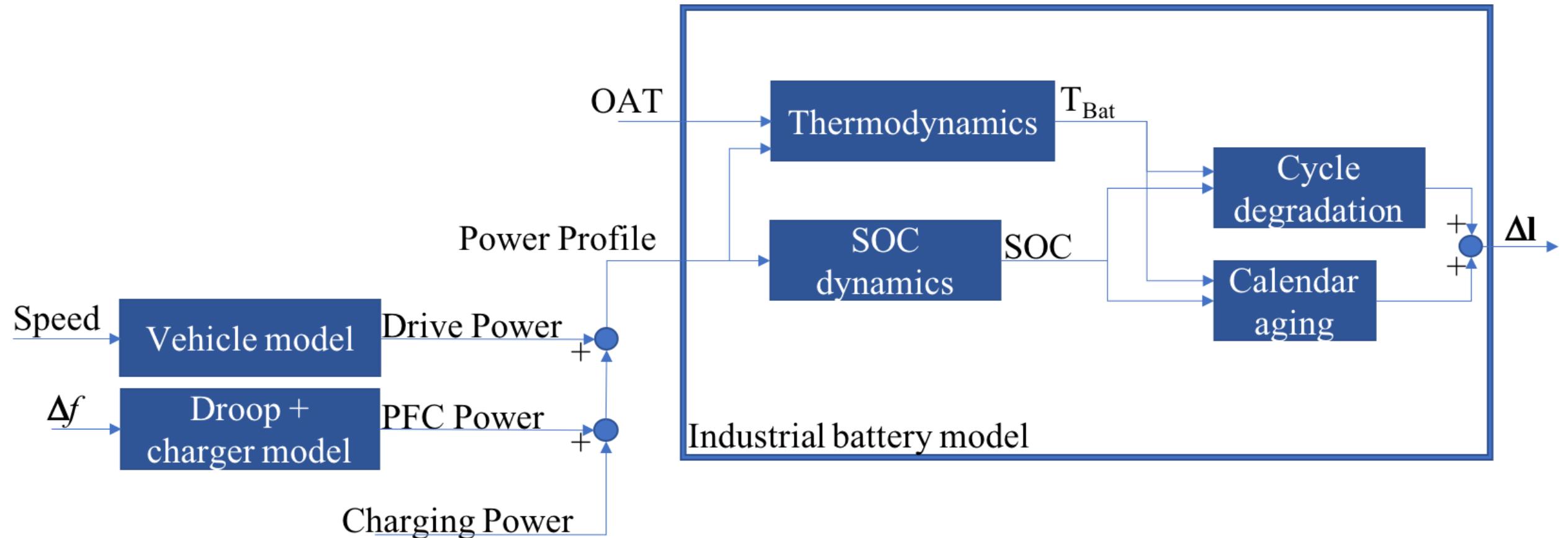


P. Keil, S. F. Schuster, J. Wilhelm, J. Travi, A. Hauser, R. C. Karl and A. Jossen, “*Calendar Aging of Lithium-Ion Batteries: I. Impact of the Graphite Anode on Capacity Fade*,” *Journal of The Electrochemical Society*, 2016.



D. Wang, J. Coignard, T. Zeng, C. Zhang, S. Saxena, “*Quantifying electric vehicle battery degradation from driving vs. vehicle-to-grid services* ” *Journal of Power Sources*, 2014

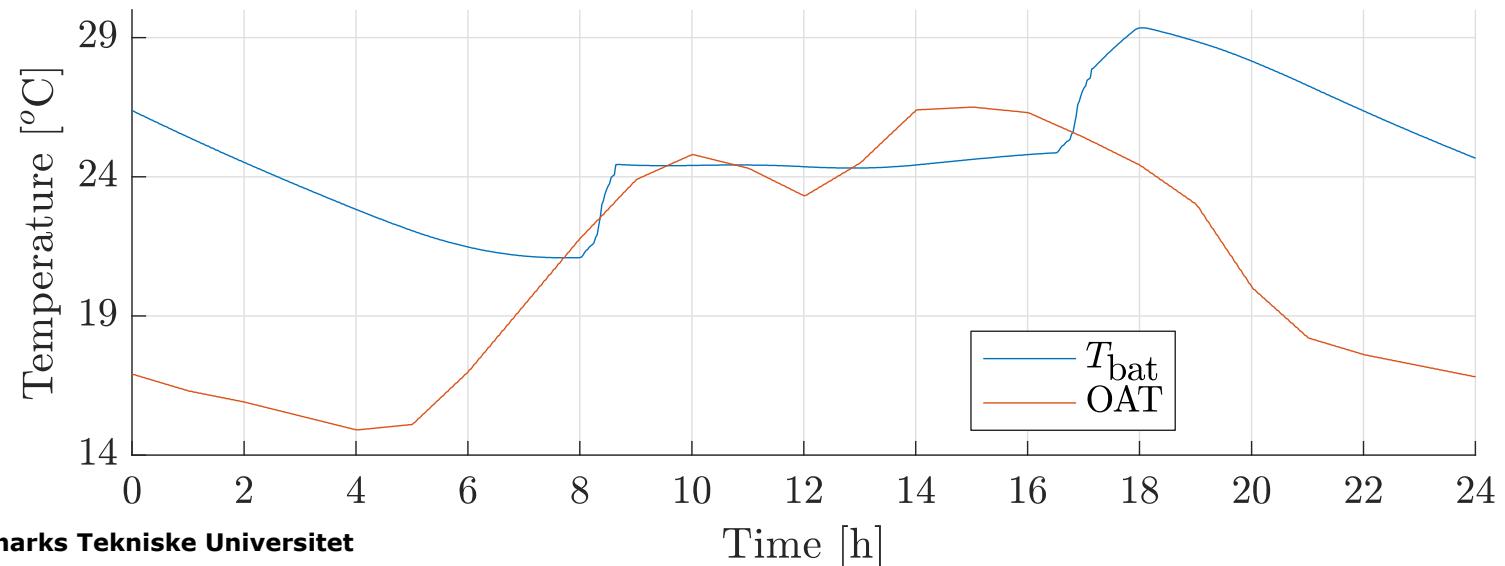
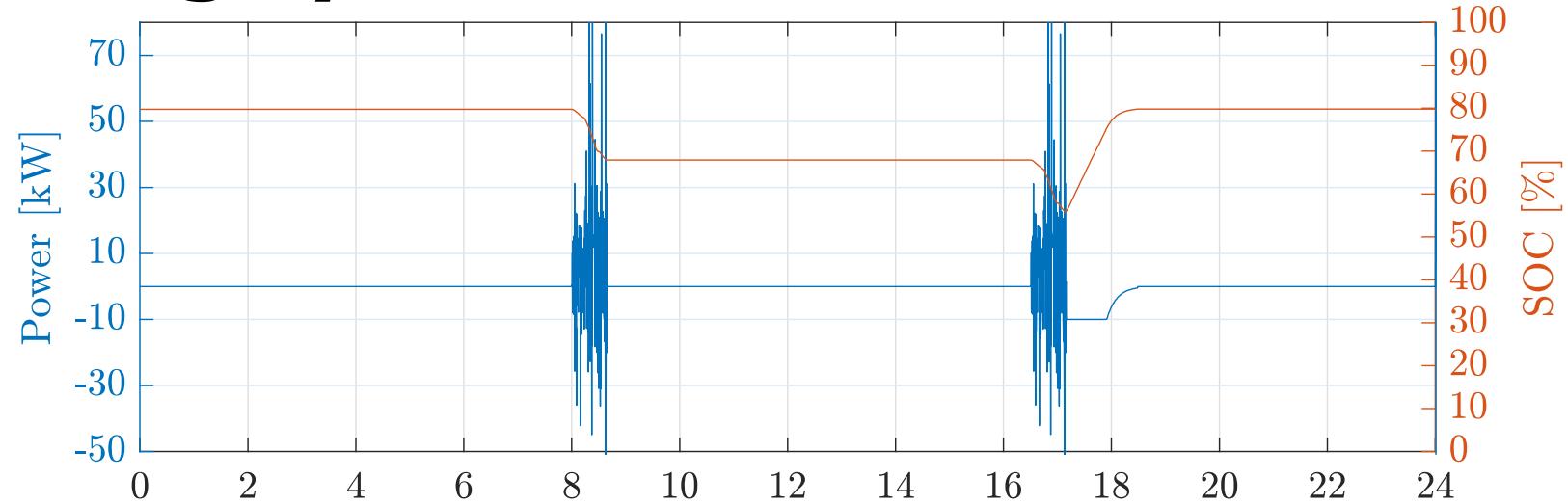
# Modelling degradation



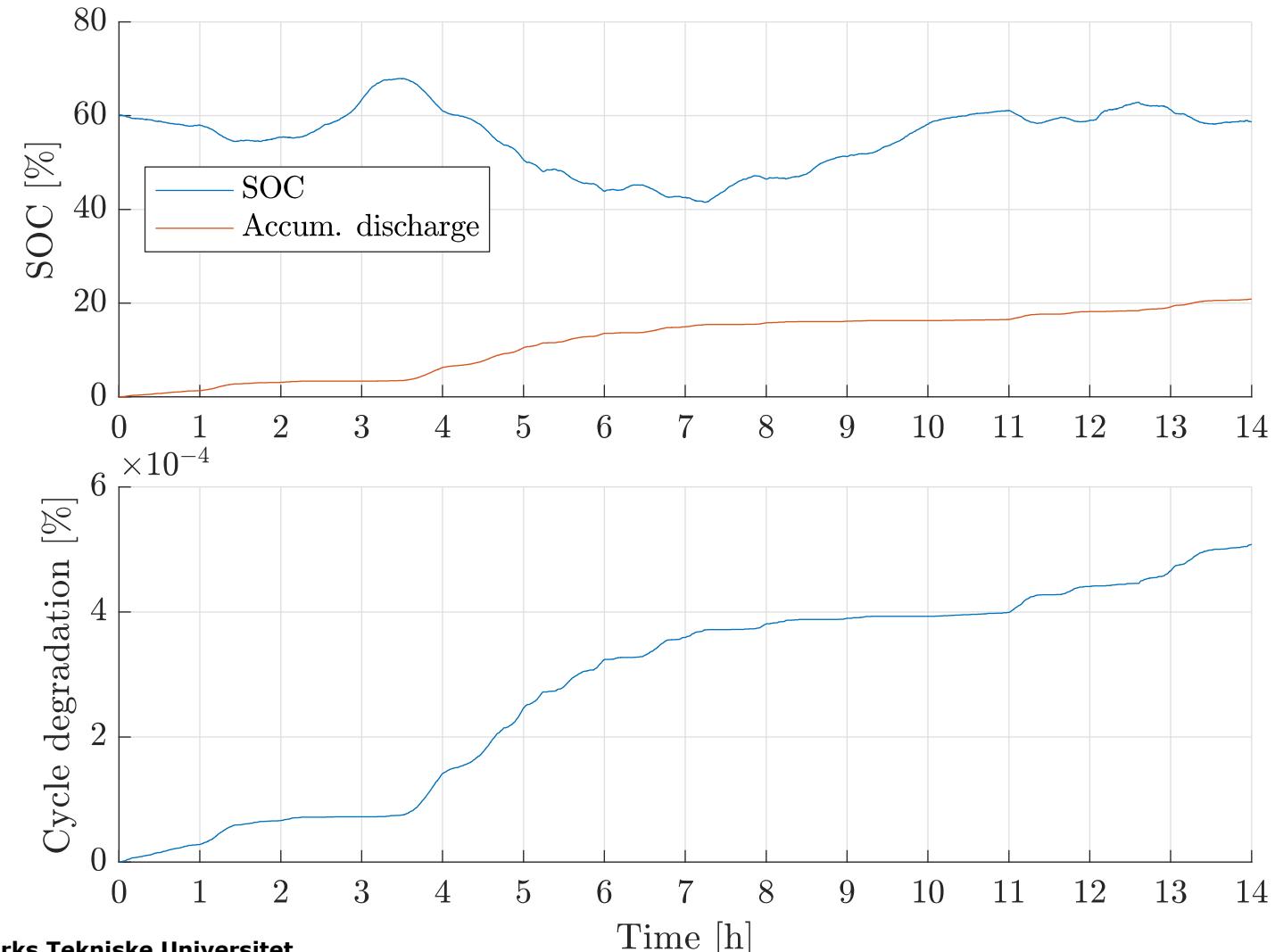
# Study cases

- Pure Calendar aging
- Degradation from driving (34 km/day)
- Frequency Regulation (14 h/day)

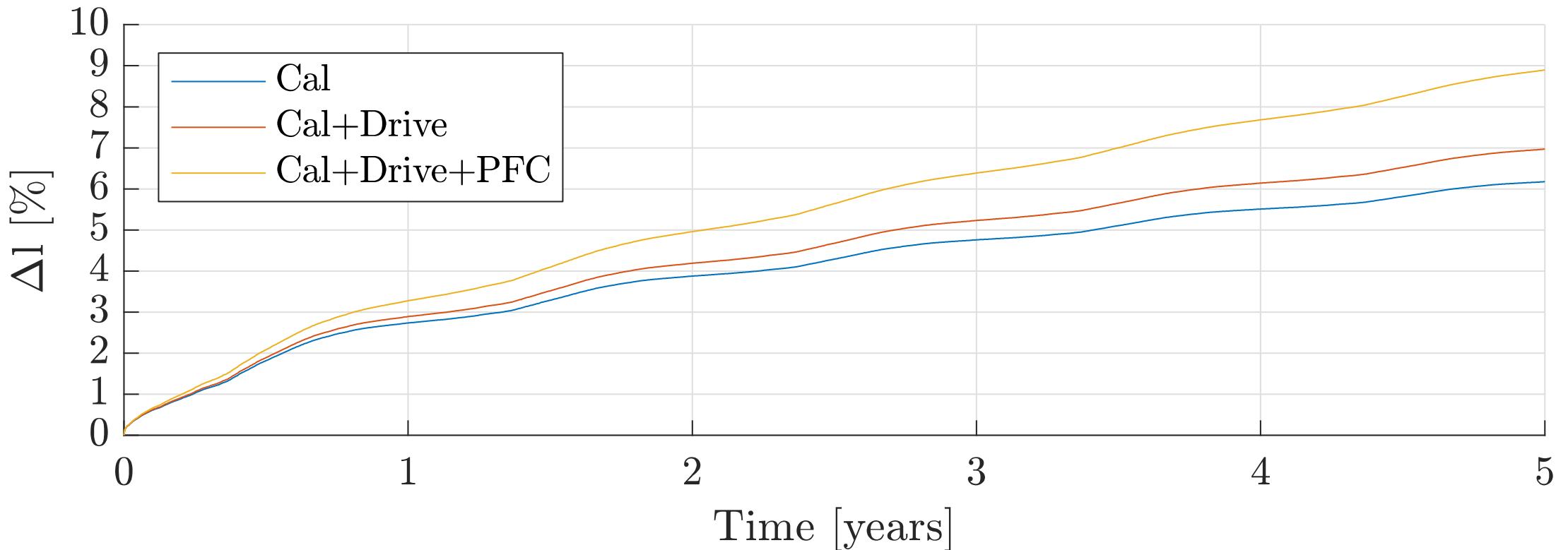
# Daily driving cycle



# Cycle degradation from frequency regulation

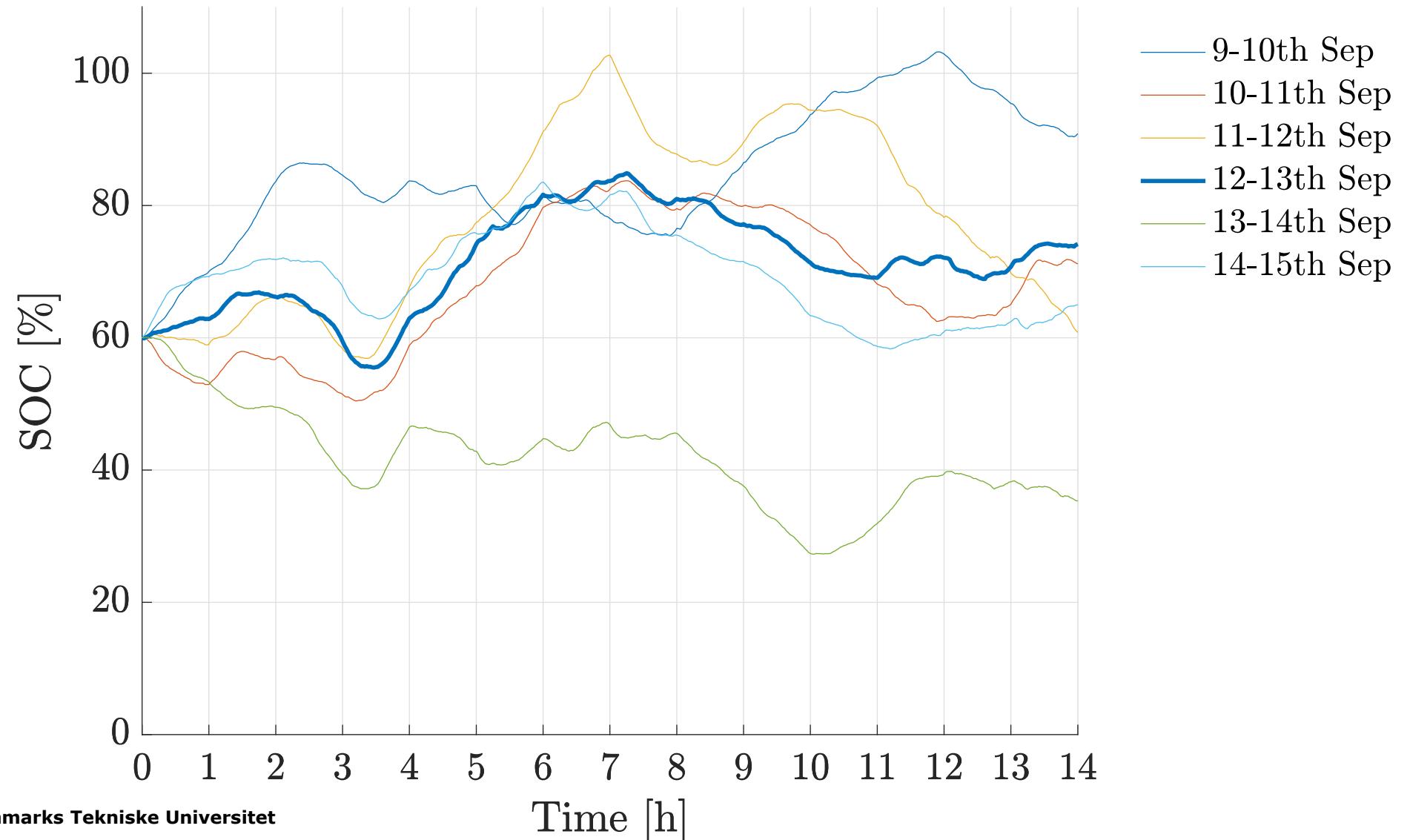


# Battery degradation



A. Thingvad & M. Marinelli, “Influence of V2G Frequency Services and Driving on Electric Vehicles Battery Degradation in the Danish Island Bornholm”, EVS31

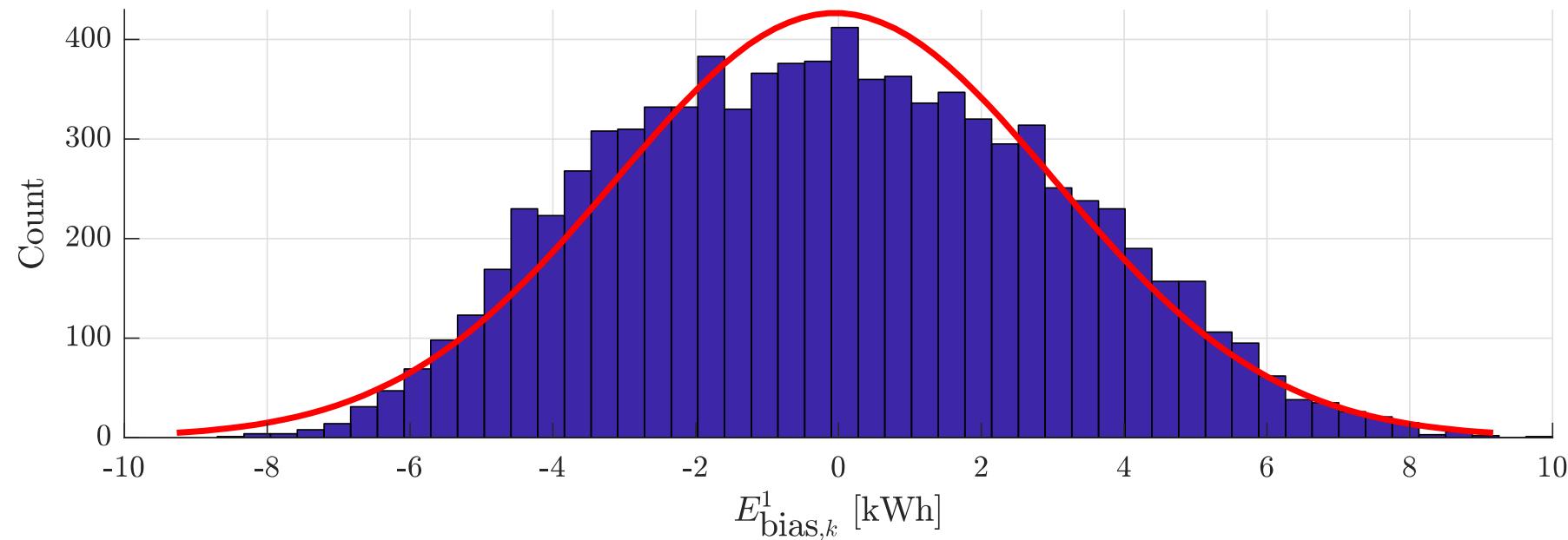
# Frequency sample



# Energy content of one hour

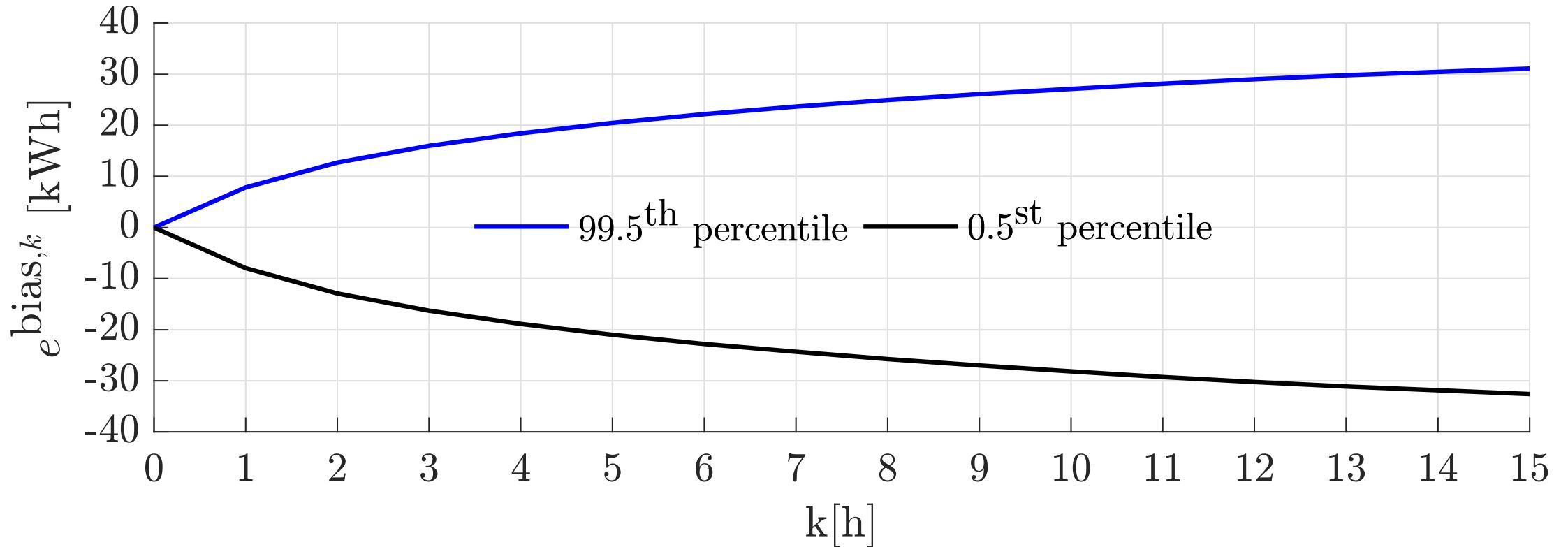
- Every hour of 2016
- Regulation capacity of +/- 10 kW
- Calculated without loss
- Worst case is +/- 10 kWh
- 99% of the cases are within +/- 8 kWh

$$E_{\text{bias},k}^1 = \sum_{t=N \cdot (k-1) + 1}^{k \cdot N} P_t \cdot t_s$$



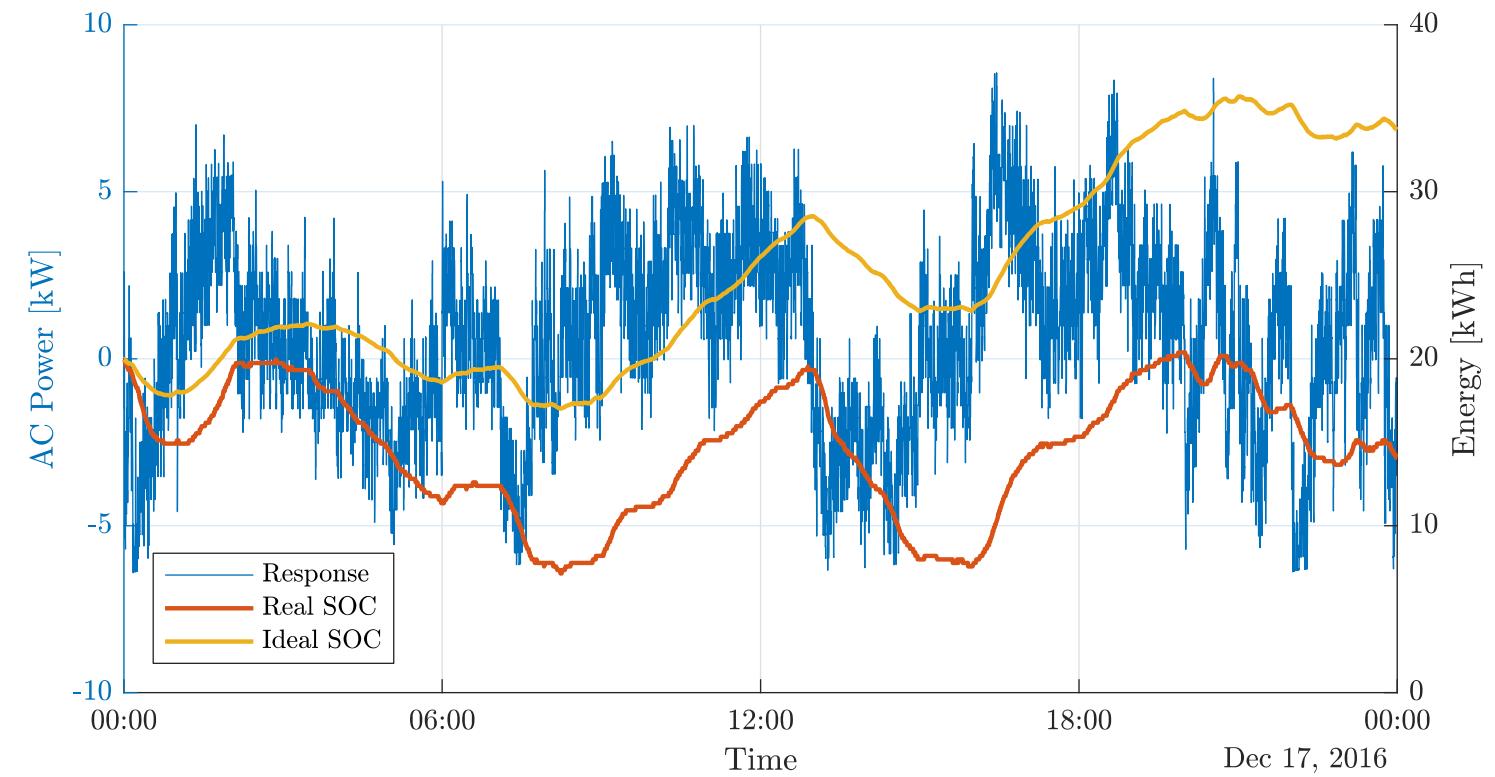
# Confidence interval

- Regulation capacity of +/-10 kW, 1-15 hours



A. Thingvad, C. Ziras, J. Hu, M. Marinelli, "Assessing the Energy Content of System Frequency and Electric Vehicle Charging Efficiency for Ancillary Service Provision", IEEE UPEC 2017

# Measurements from Frederiksberg Forsyning



# Optimal regulation schedule

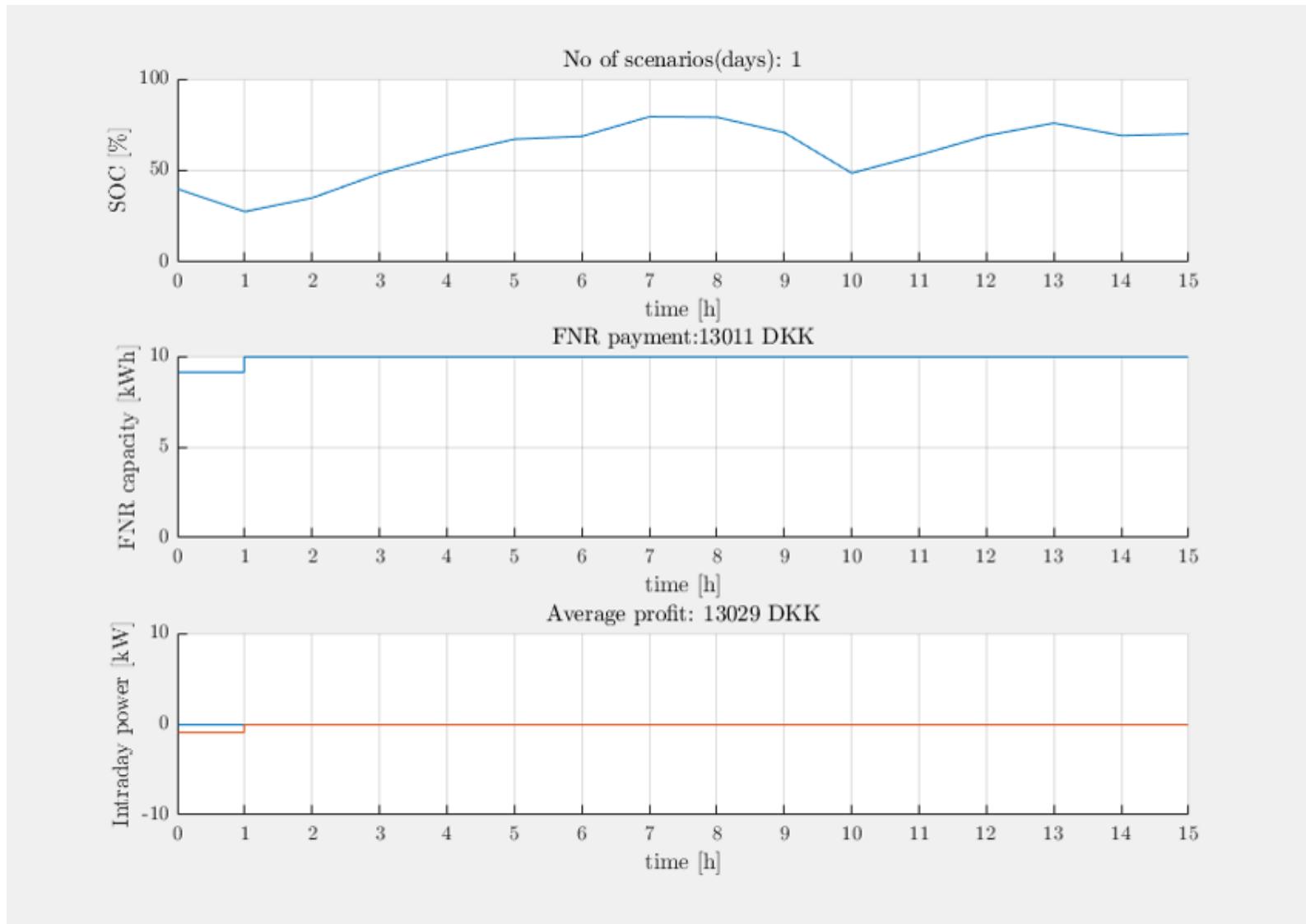
$$\min_{SOC, P^c, P^d, P^r} \sum_{\omega} \sum_{h=1}^{15} c_h^E P_{h,\omega}^c - c_h^E P_{h,\omega}^d - c_h^r P_h^r$$

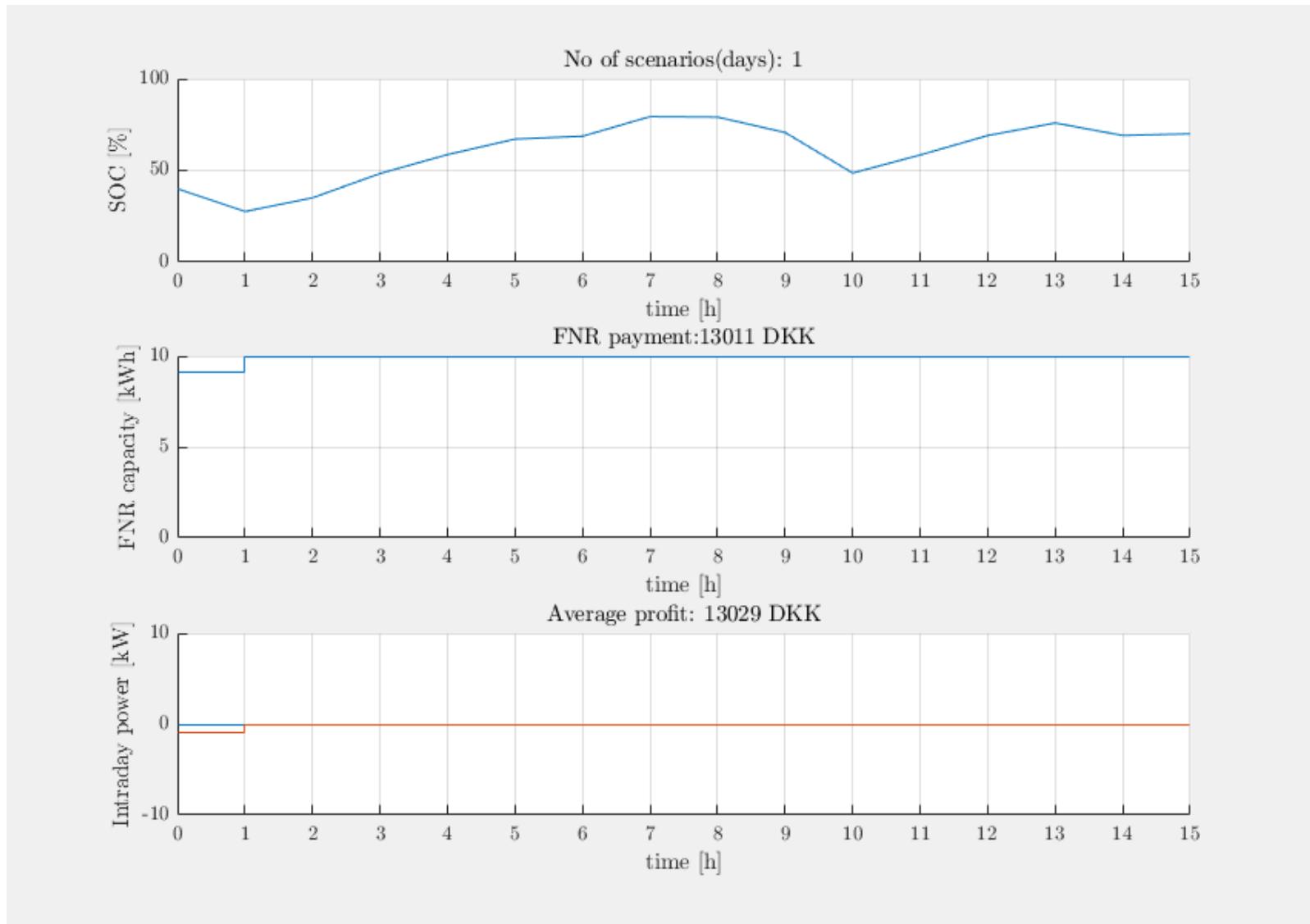
$$P_{h,\omega}^c + P_{h,\omega}^d + P_h^r \leq P_{\max}$$

$$P_{h,\omega}^c \geq 0 \quad , \quad P_{h,\omega}^d \geq 0 \quad , \quad P_h^r \geq 0$$

$$SOC_{h+1,\omega} = SOC_{h,\omega} + [P_{h,\omega}^c \eta_c + e_{h,\omega}^{\text{bat}} P_h^r - P_{h,\omega}^d \frac{1}{\eta_d}] \frac{\Delta T}{Q_n}$$

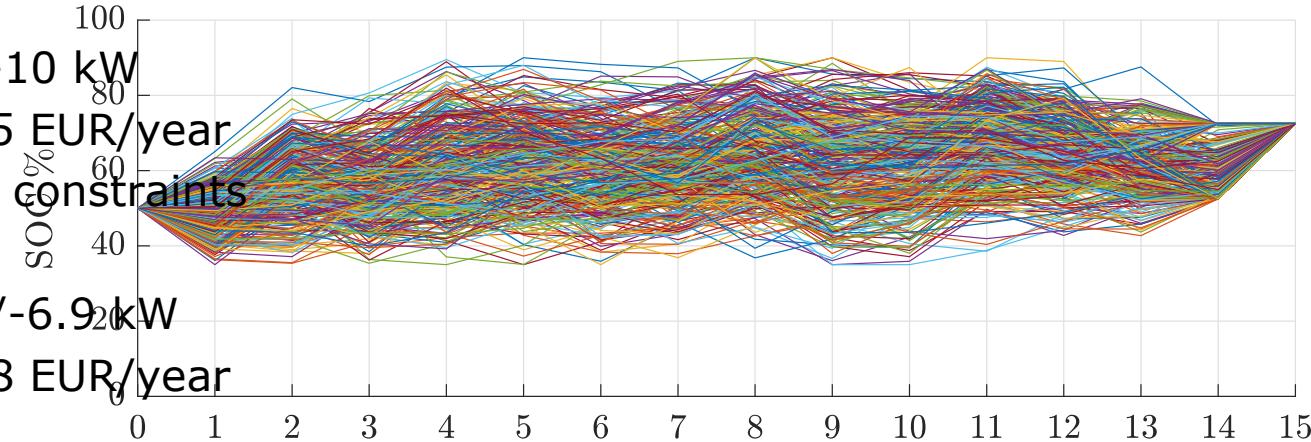
$$\underline{SOC} \leq SOC_{h,\omega} \leq \overline{SOC}$$



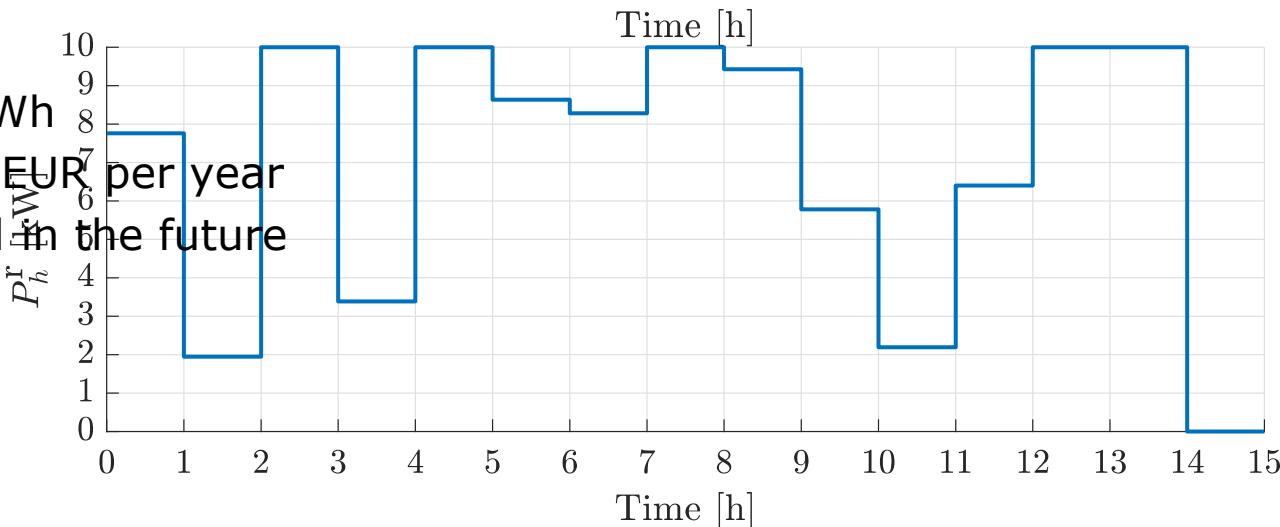


# Scheduling result

- V2G 15 hours of PFC +/-10 kW
  - Yearly revenue: 1395 EUR/year
  - 88% violated energy constraints
- V2G schedule on avg. +/-6.9 kW
  - Yearly revenue: 1118 EUR/year



- Yearly energy loss: 2.6 MWh
  - 0.08 EUR/kWh → 208 EUR per year
  - Expected to decrease in the future
- Frequency regulation schedule



# Battery degradation

- Battery degradation study
  - Yearly Throughput: 5.8 MWh
  - Yearly full cycles with 40 kWh battery: 73
  - → 0.4% cycle degradation per year from PFC
- Schedule
  - Yearly Throughput: 12.2 MWh
  - Yearly full cycles with 40 kWh battery: 153
  - → 0.8 % cycle degradation per year from PFC

$$E_{\text{tp}} = \sum_{h=1}^{15} (P_{k,h}^c \eta_c + |e_{k,h}^{\text{bat}} P_h^r| + P_{k,h}^d \frac{1}{\eta_d}) \Delta T - \sum_{k=1}^{365} E_{\text{drive}}$$

# Capacity tests



# Conclusion

- No more than +/-6.9 kW PFC capacity can be delivered with a 10 kW charger and a 40 kWh battery.
  - Up to 1118 EUR/ year in capacity payment
  - Even with low electricity price the losses are significant but can be expected to decrease.
- Calendar aging is the most important component
- Degradation from PFC is low but should still be taken into account
- The next step is more experimental validation and economic analysis

# Thank you!

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