Distributed Battery Storage: Operation and Integration

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Frontiers in Energy Research Talk

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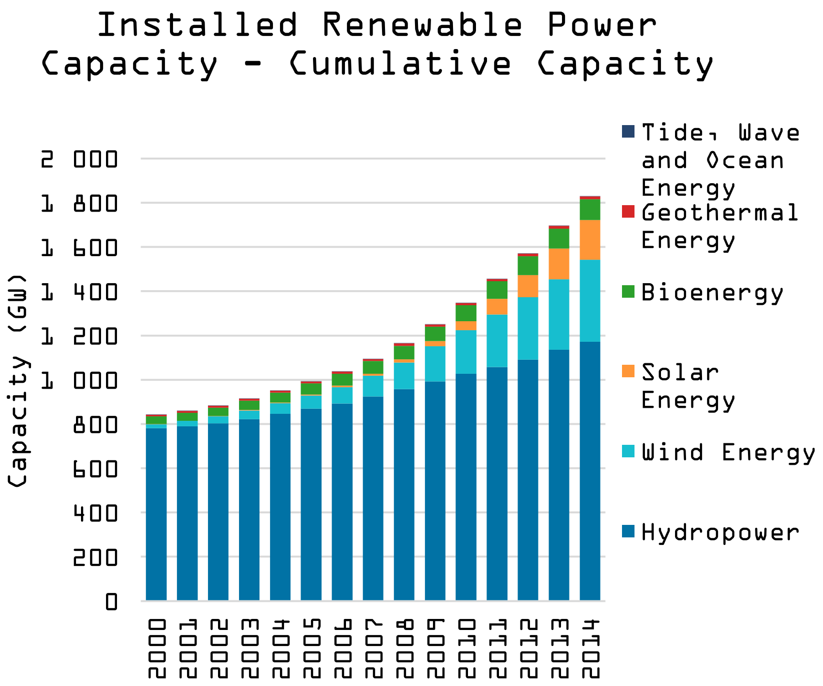
- Since Mai 2012 PhD student at Power Systems Laboratory (PSL)
- Interests Integration of Renewables in LV networks

Introduction

- Increase of intermittent renewable energy sources (RES) in future
    - Short and long term storage facilities are needed to balance load demand and generation
- Photovoltaics (PV) mainly installed in low voltage (LV) networks
    - Grid capacity is limited
    - Distribution System Operators (DSOs) will face congestions in the distribution grid in future

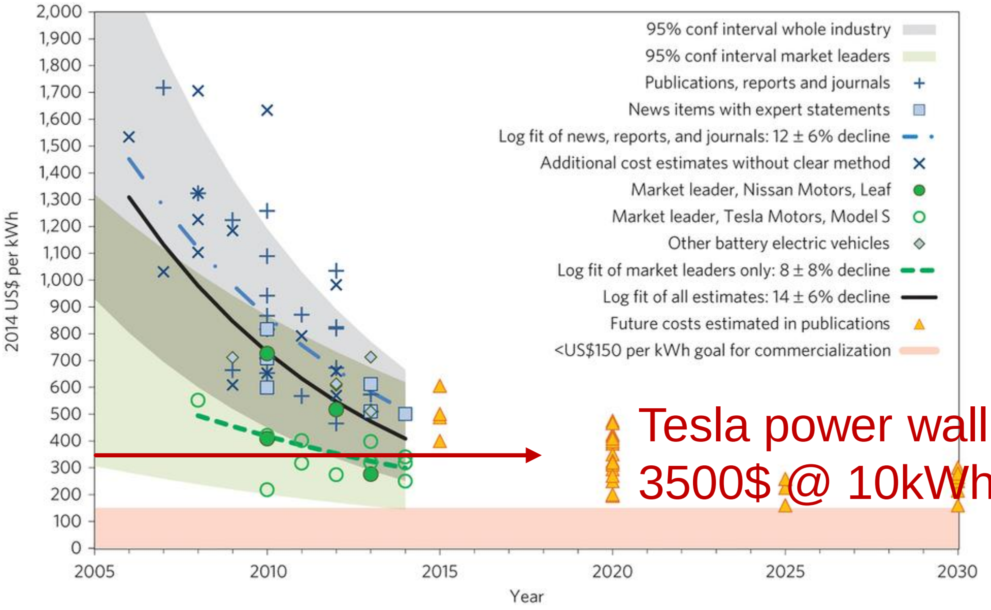


Installed Renewable Power Capacity - Cumulative Capacity

From www.irena.org/resource

Batteries a solution?

- Battery costs in future



Tesla power wall
3500$ @ 10kWh

From *Rapidly falling costs of battery packs for electric vehicles*
Björn Nykvist, Måns Nilsson
Nature Climate Change 5, 329–332 (2015)

- Batteries can deal with those challenges, but…
  - they have high investment costs
  - at the moment they are not economically viable
- To enhance profitability run multiple services on batteries

Potential applications for batteries

- Grid security
  - Local grid support (power quality, prevent thermal overloadings)
  - System wide services (ancillary services e.g. frequency control)

- Economically incentivized
  - Increase PV self consumption to lower electricity bill
  - Peak shifting for industrial costumers
  - Arbitrage on tariff schemes (buy low, consume high)
  - Balancing RES forecast errors e.g. wind farms, balancing groups to enhance profitibility
  - Pooling in energy market («virtual power plant»)

Related research areas

Outline

- Battery models for power system applications
- Optimal Power Flow (OPF) in distribution grids
- Optimal grid operation with batteries
- Optimal sizing and placement of batteries
- Conclusion

Outline

- **Battery models for power system applications**
- Optimal Power Flow (OPF) in distribution grids
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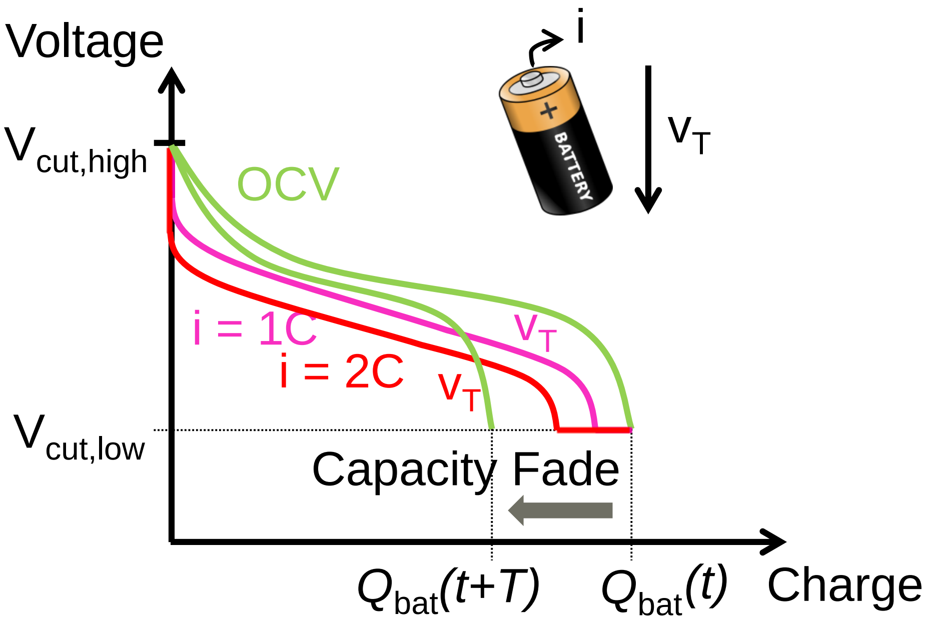
Battery models for power systems

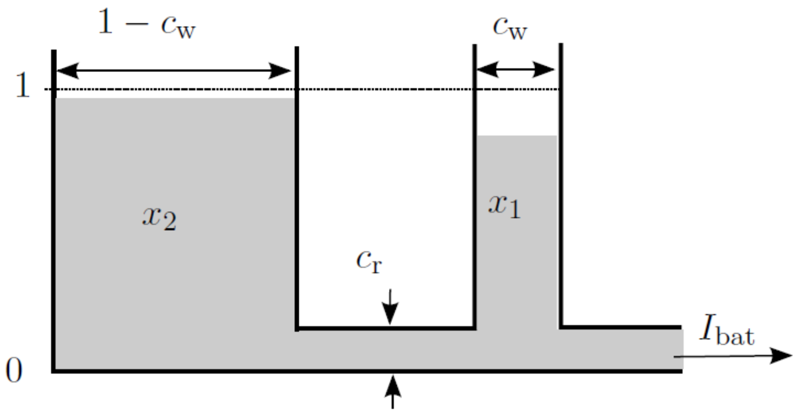
- Challenges
  - Need of functional models that capture relevant dynamics
  - Simple integrator based models often not sufficient
- Fast transients «rate capacity effect»
- Slow transients degradation

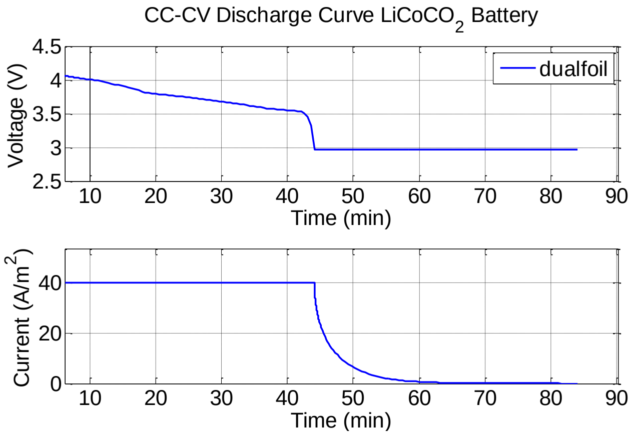
Battery principles



- Open Circuit Voltage (OCV) according to Nernst Equation
- Rate Capacity effect
  - Usable capacity decreases at high battery power
  - Diffusion limitation causes additional voltage drop
- Capacity fade process
  - Depends on operational management
  - Irreversible

Modeling a battery’s fast dynamics



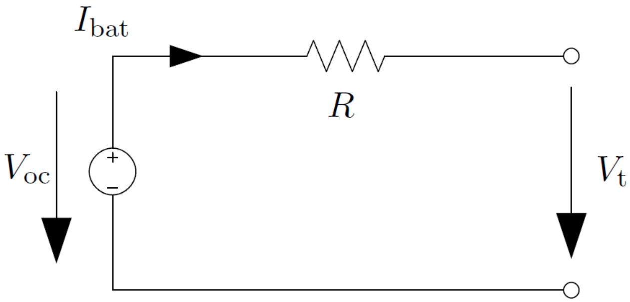


J. F. Manwell and J. G. McGowan, “Lead acid battery storage model for hybrid energy systems,” Solar Energy, vol. 50, no. 5, pp. 399 – 405, 1993

$$\underbrace{\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}}_{\dot{\boldsymbol{x}}} = \underbrace{\begin{bmatrix} -\frac{c_r}{c_w} & \frac{c_r}{1-c_w} \\ \frac{c_r}{c_w} & -\frac{c_r}{1-c_w}\end{bmatrix}}_{\boldsymbol{A}} \boldsymbol{x} - \begin{bmatrix} Q_{bat}^{-1}\\ 0\end{bmatrix} \boxed{I_{bat}},$$

$$\boxed{V_t} = f_{ocv}\left(\frac{x_2}{1-c_w}\right) - RI_{bat} \quad ,$$

$$\text{SOC} = x_1 + x_2$$

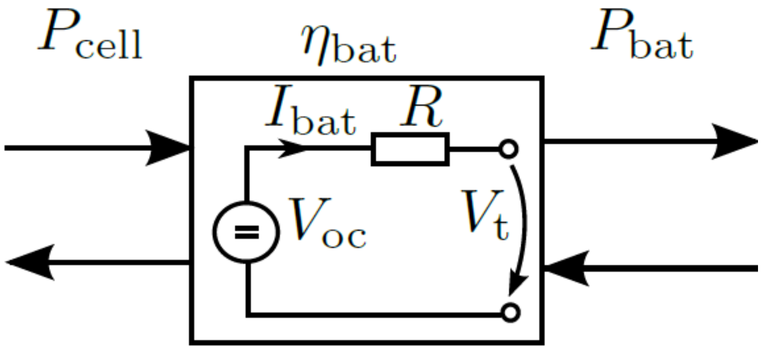


Measurable quantities for system identification

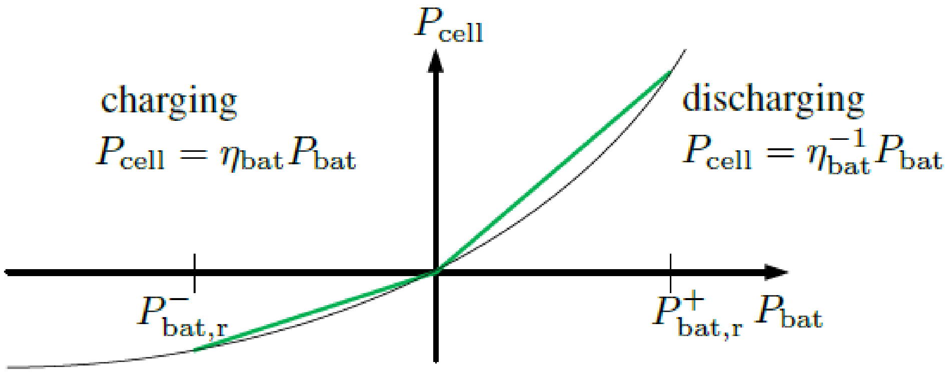
P. Fortenbacher, J. Mathieu, and G. Andersson, “Modeling, identification, and optimal control of batteries for power system applications,” in *Proceedings of PSCC*, 2014

Linear power-based models for control

- Neglecting power converter dynamics
- Linearize cell powers for charging and discharging
- OCV constant



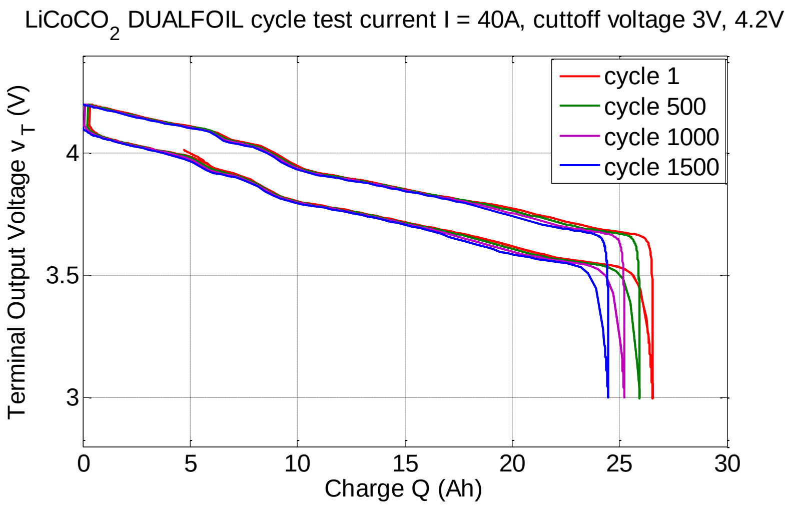
- Linear basic model
- Linear extended model



DUALFOIL model as a real reference

- Ion diffusion processes (Fick’s Law) with PDEs
- Electrode kinetics
- Solution of Differential Algebraic Equations (DAE)
- Properties
  - Technology (Li-Ion, NiMH)
  - Wide Range of cathode and anode materials
    - $LiCoCO_2$,$LiMnO_2$, …
  - FORTRAN

- Capacity fade process included (side reaction framework)

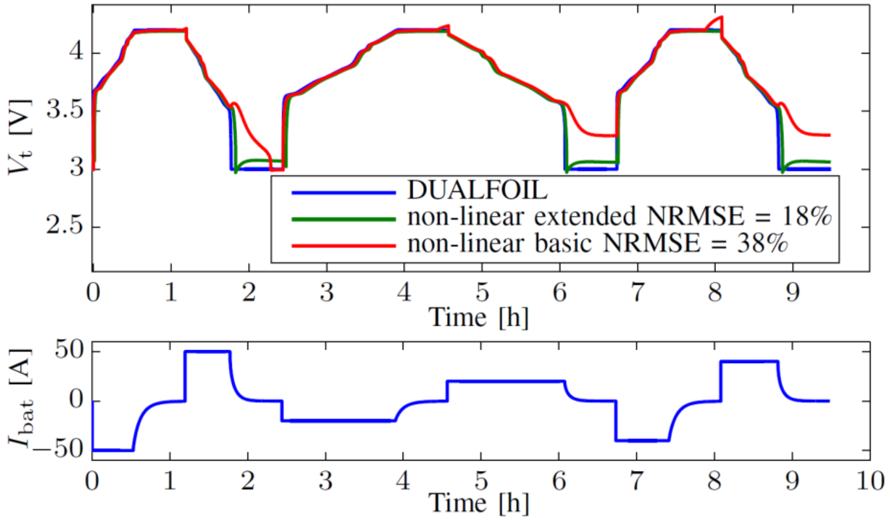


M. Doyle and J. Newman, “Analysis of capacity-rate data for lithium batteries using simplified models of the discharge process,” Journal of Applied Electrochemistry, vol. 27, no. 7, pp. 846–856, 1997.

Identification results

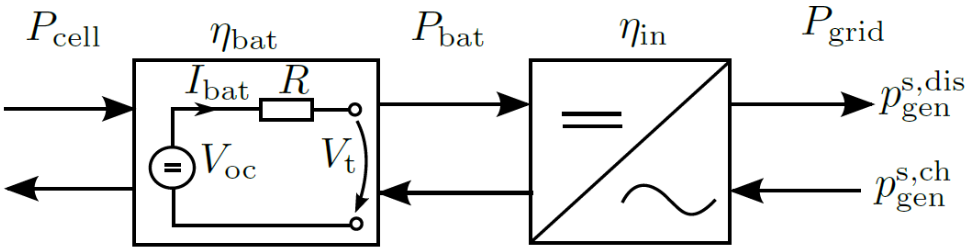
- Solve NLS Problem for non-linear models
- Calculate parameters for linear models

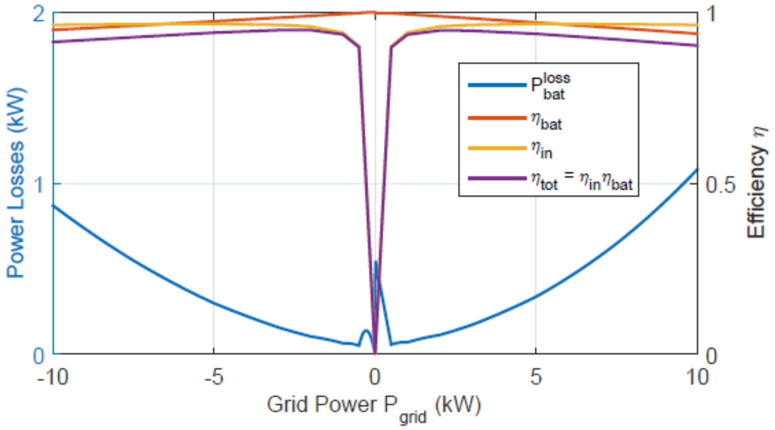
Parameter	Value	Description
R	1.5mΩ	Internal Resistance
Q_{bat}	31.25 Ah	Charge capacity
c_{w}	0.13	Charge well factor
c_{r}	1e-3 sec^{-1}	Recovery factor
η_{gen}	0.97	Discharge Efficiency
η_{load}	0.98	Charge Efficiency
C_{bat}	120 Wh	Energy Capacity



Model	NRMSE [%]	
	SOC	Voltage
Non-Linear basic	0	38
Non-Linear extended	0	18
Linear basic	3	98
Linear extended	3	59

More detailed battery models with inverter





- Battery efficiency with Thevenin circuit equivalent
- Inverter efficiency with standard characteristics from datasheet

- Non-convex loss function for total losses
- Mixed Integer programming (MIP) problem

Philipp Fortenbacher, Johanna L. Mathieu and Göran Andersson, Optimal Real-Time Control of Multiple Battery Sets for Power System Applications, IEEE PES PowerTech 2015, Eindhoven, Netherlands, 29 June-2 July 2015 .

Modeling slow battery dynamics - degradation

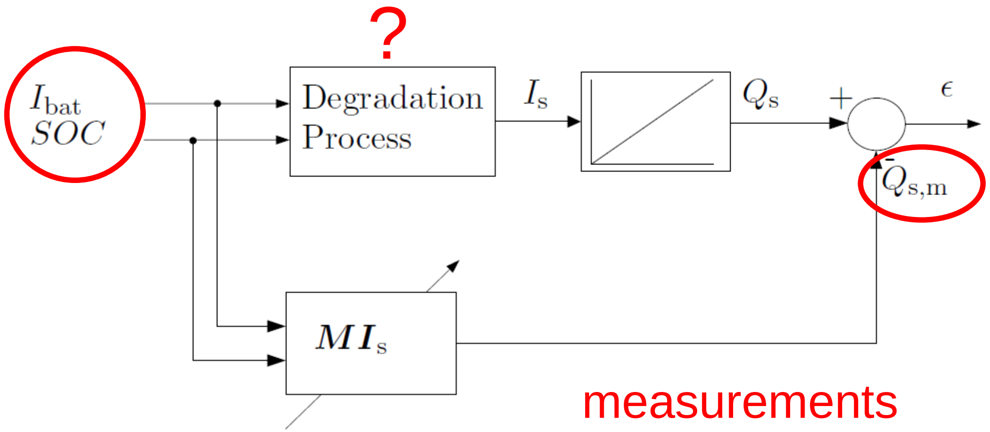
- Capacity loss: irreversible chemical side reactions transform cyclable ions into solid components

- Capacity loss process dependent on operational management

$$I_{\mathrm{s}} = -\dot{Q}_{\mathrm{bat}} = f(V_{\mathrm{oc}}, I_{\mathrm{bat}}, \vartheta)$$

- Degradation process not directly measurable

Degradation ID Method

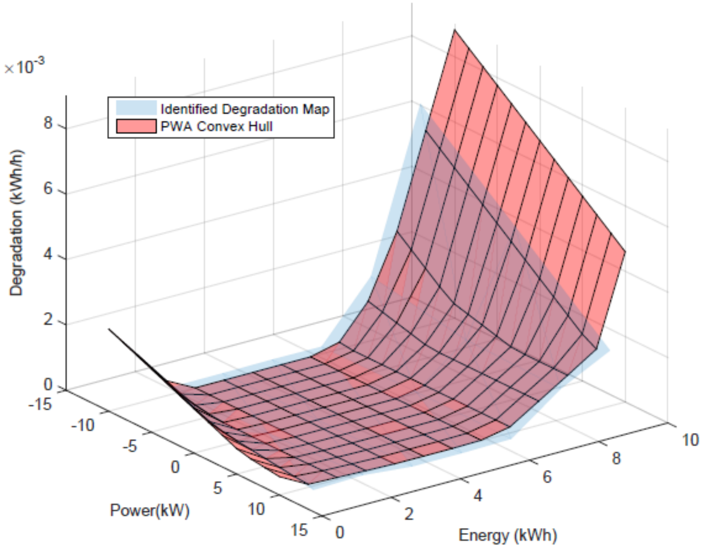


$$\hat{\boldsymbol{I}}_{\text{s}} = \arg\min_{\hat{\boldsymbol{I}}_{\text{s}}} \|\boldsymbol{M}\hat{\boldsymbol{I}}_{\text{s}} - \boldsymbol{Q}_{\text{s}}\|_2^2$$
$$\text{s.t.} \quad \hat{\boldsymbol{I}}_{\text{s}} > 0 \quad .$$

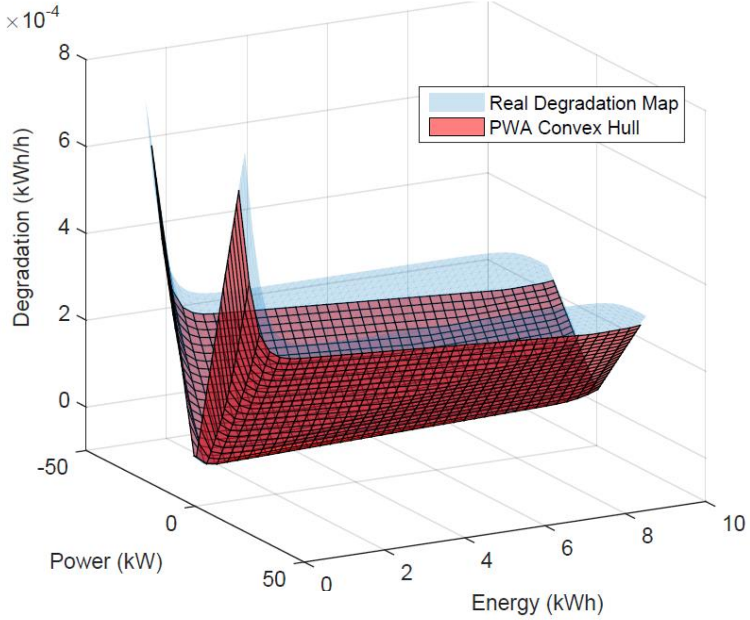
- Use arbitrary forcing pattern to obtain linearly independent Matrix M
- Rank(M) equals number of measurements needed to obtain an unique solution
- Solve for side current $\boldsymbol{I}_{\text{s}}$ to get degradation map

Degradation maps

- LiCoO2 based on high-fidelity model DUALFOIL [6]



- LiFePO4 based on experimental cycling [14]



- Convex Approximation

$$\tilde{J}_{\text{deg}} = \max\left(\begin{bmatrix}\boldsymbol{a}_1 & \boldsymbol{a}_2 & \boldsymbol{a}_3\end{bmatrix}\begin{bmatrix}P_{\text{bat}}\\ SoE\\ C_{\text{E}}\end{bmatrix}\right)$$

Implications for control strategies

- Fast transient models are needed when we need to control batteries in real-time
- Capacity fade is a slow process and depends on the operational management
  - Potential for intelligent control strategies
- Linear models and convexification of degradation maps allow for efficient control algorithms (e.g. lower hardware requirements for controllers)

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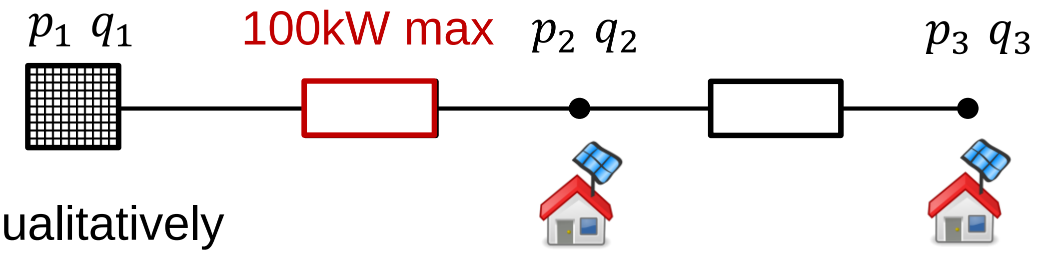
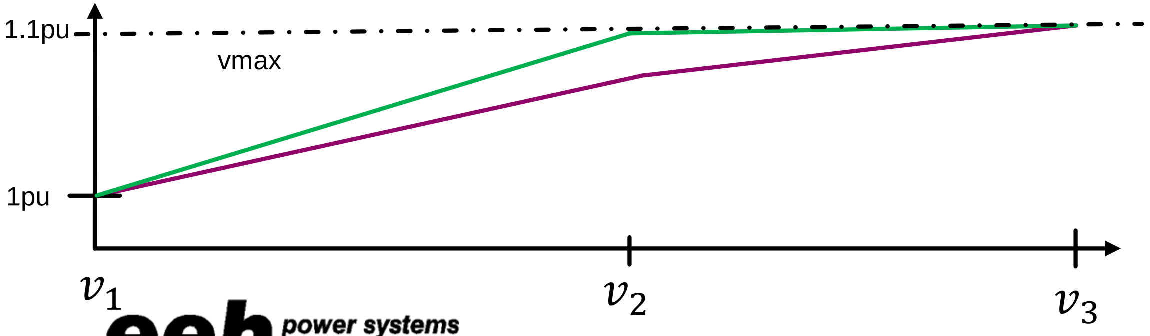
Optimal Power Flow (OPF) in distribution grids



- Maximize PV infeed
- Subject to
  - Thermal Constraints
  - Voltage Constraints

qualitatively

-200kW	100kW	100kW	
-100kW	50kW	50kW	
-50kW	25kW	25kW	
-80kW	80kW	0kW	Optimal active power curtailment (APC)
-90kW/-10kVar	80kW	10kW/10kVar	APC + optimal reactive power control (RPC)



Optimal Power Flow for grid operation

- Nowadays:
  Distribution System Operators (DSOs) have limited information to run the grid
  - Rule based methods to ensure grid security (V/Q characteristics, ripple control)
- In future:
  DSOs can use OPF to exploit the full potential of the underlying network (e.g. optimal RPC, APC, optimal BESS strategies)
  - Mitigation of investments for grid expansion
  - But requires communication infrastructure

Motivation for linearized OPF methods

- Computational burden is high to calculate non-linear AC-OPF in real-time operation
- A planning framework has also to reflect the OPF operational strategy
  - This means: long planning horizons and intertemporal coupling (storage) lead to intractable planning problems

- Linearized version of the AC-OPF can help to make the problem tractable
  - DC-OPF is not meaningful for LV networks

Recasting AC-OPF to FBS-OPF

- Standard AC-OPF

$$\begin{aligned} J(\boldsymbol{x}^*) = \min_{\boldsymbol{x}} \quad & f_p(\boldsymbol{p}_{\text{gen}}) + f_q(\boldsymbol{q}_{\text{gen}}) \\ \textit{s.t.} \quad & \boldsymbol{h}(\boldsymbol{x}) \leq 0 \\ & \boldsymbol{g}(\boldsymbol{x}) = 0\,. \end{aligned}$$

- Assumptions:
- Voltage angles are small
- Radial network
- R/X ratio high

- Recast to Forward Backward Sweep (FBS)-OPF

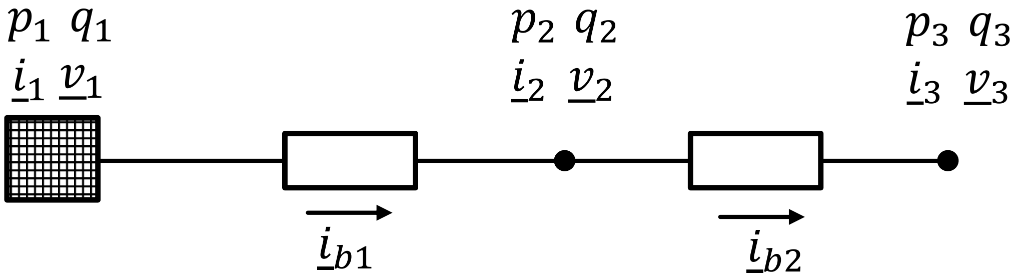
$$\begin{aligned} \min_{\boldsymbol{x}} \quad & \boldsymbol{f}^{con}(\boldsymbol{p}_{\text{gen}}) \\ \boldsymbol{s.t.} \quad & \boldsymbol{A}_{\text{in}}\boldsymbol{x} \leq \boldsymbol{b}_{\text{in}} \\ & \boldsymbol{A}_{\text{eq}}\boldsymbol{x} = \boldsymbol{b}_{\text{eq}}. \end{aligned}$$

- Piecewise-linear loss approximation
- Linear voltage approximation
- Linear Programming (LP) Problem

Accepted at PSCC16: P. Fortenbacher, M. Zellner "Optimal Sizing and Placement of Distributed Storage in Low Voltage Networks"

Forward Backward Sweep (FBS) Load Flow

- Definitions



- Node currents

$$\underline{\boldsymbol{i}}^{n\times1} = \underbrace{\mathrm{diag}\{1/\underline{v}_1,\ldots,1/\underline{v}_n\}^*}_{\underline{\boldsymbol{V}}_{\mathrm{df}}}[\boldsymbol{p}+j\boldsymbol{q}]^*$$

- Branch currents

$$\underline{\boldsymbol{i}}_{\mathrm{b}}^{l\times1} = \boldsymbol{M}_{\mathrm{f}}\ \underline{\boldsymbol{i}}$$

- Bus Injection to Branch Current (BIBC) Matrix

$$\boldsymbol{M}_{\mathrm{f}} = \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{M} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$$

- Power Flow Algorithm
  - Iterate *k*
    - Forward Stage
    - $\underline{\boldsymbol{i}}^k = \underline{\boldsymbol{V}}_{\mathrm{df}}^{*k}\ [\boldsymbol{p} - j\boldsymbol{q}\ ]$
    - Backward Stage
    - $\underline{\boldsymbol{v}}^k = \boldsymbol{v}_s + \boldsymbol{M}^T\boldsymbol{Z}\boldsymbol{M}_{\mathrm{f}}\underline{\boldsymbol{i}}^k$

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Optimal operation

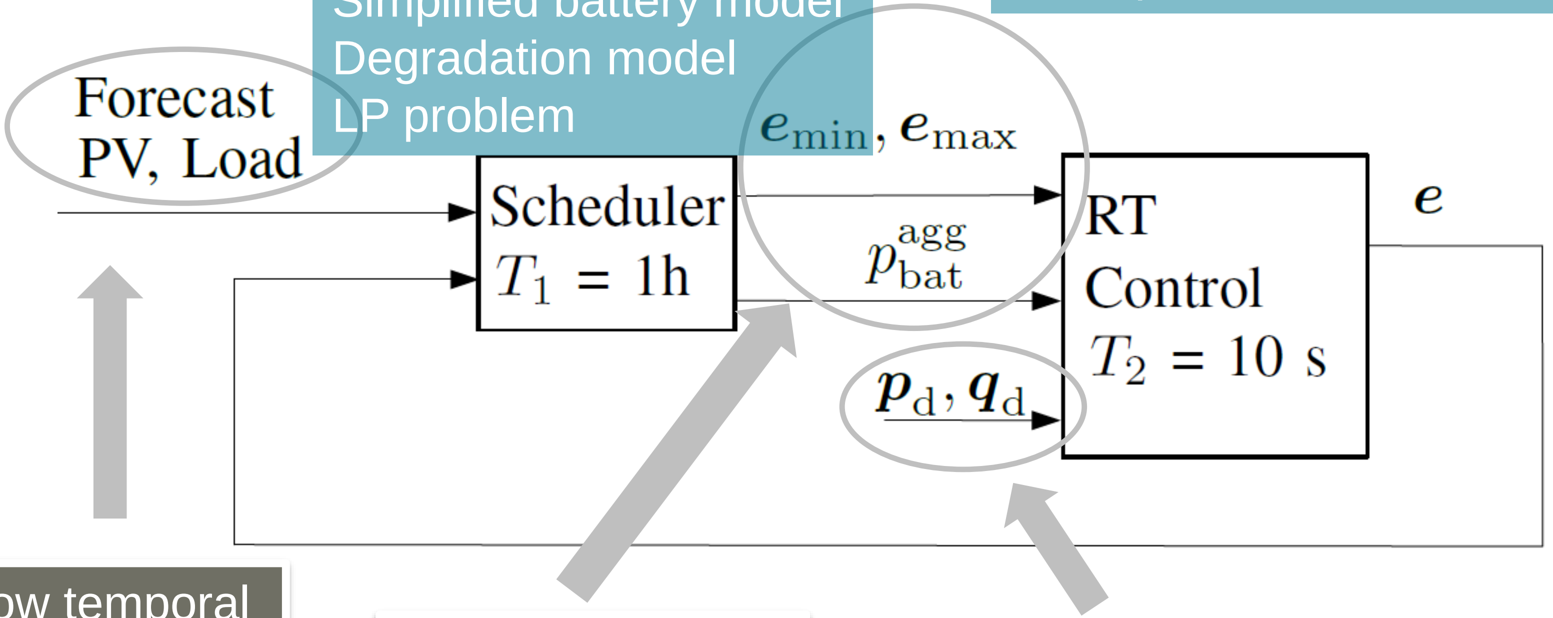
- Control challenges
  - Link real time (RT) domain with operational planning domain
    - Battery dynamics, Grid security on short time scale (10sec -10 min)
    - PV, and load forecast on higher time scales (~1h)
  - Computational complexity

- Solution approach
  - Two-stage control strategy: scheduler and RT-control entity

Control architecture

Robust Model Predictive Control (MPC)
FBS-OPF
Simplified battery model
Degradation model
LP problem

Enhanced battery model
FBS-OPF
MPC one step
MILP problem



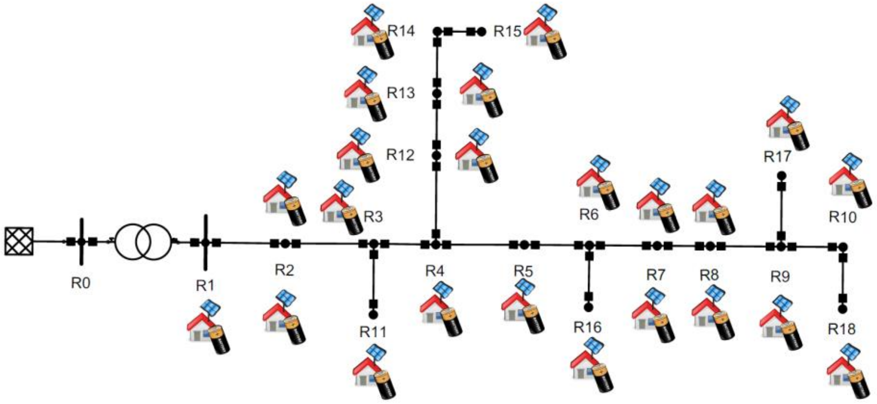
Low temporal resolution

Storage allocation

Real-time measurements from grid

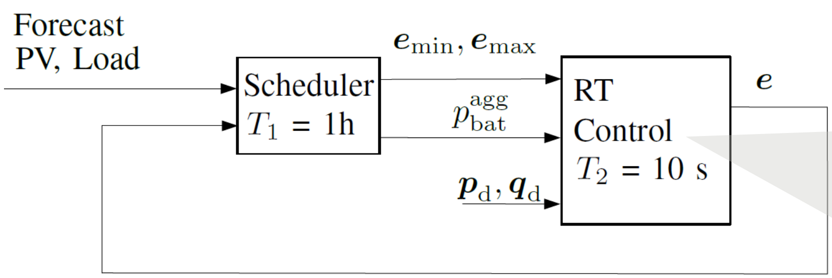
Case study operation

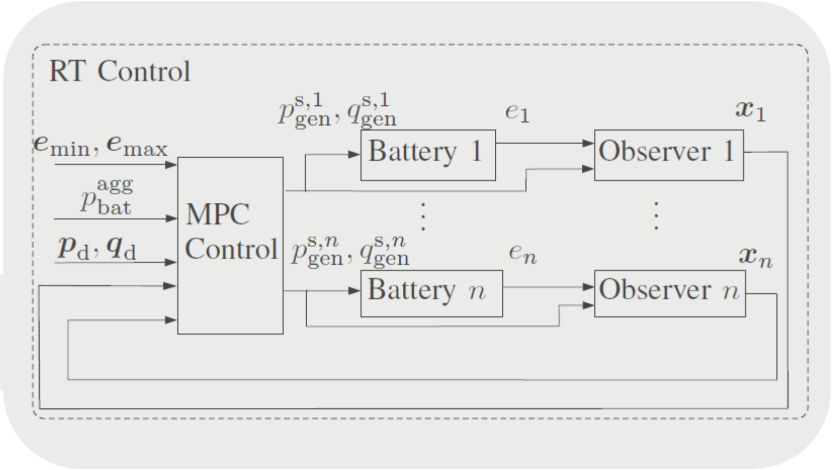
- DSO wants to invest in storage to defer line upgrade
- Control Objective
  - Maximize PV utilization (no PV curtailment) and minimize battery degradation
- Subject to
  - Grid constraints (thermal line overloading and voltage) in RT
  - Storage constraints in RT
- DUALFOIL model used in place as a real battery model in RT



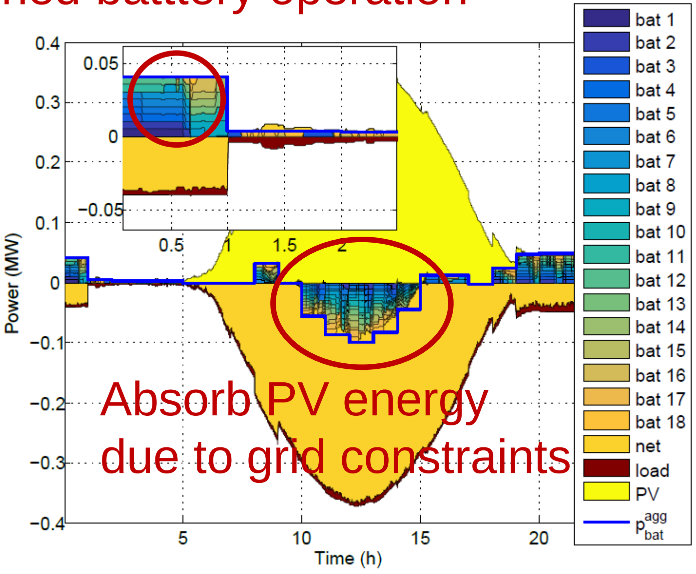
Scenario Definition	
Storages	18
Storage Power/ Capacity	10kVA @ 20kWh
PV share	100% (19)
PV power	20kVA
Busses	19
Households	18

RT-dispatch results



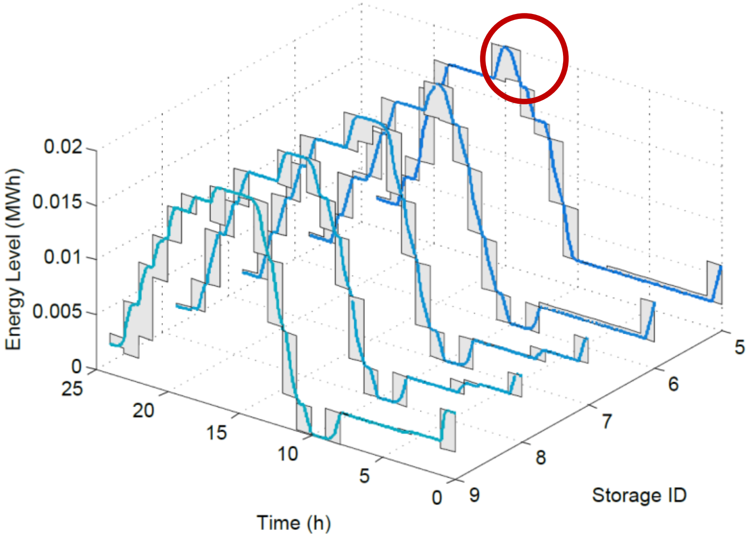


Switched batttery operation



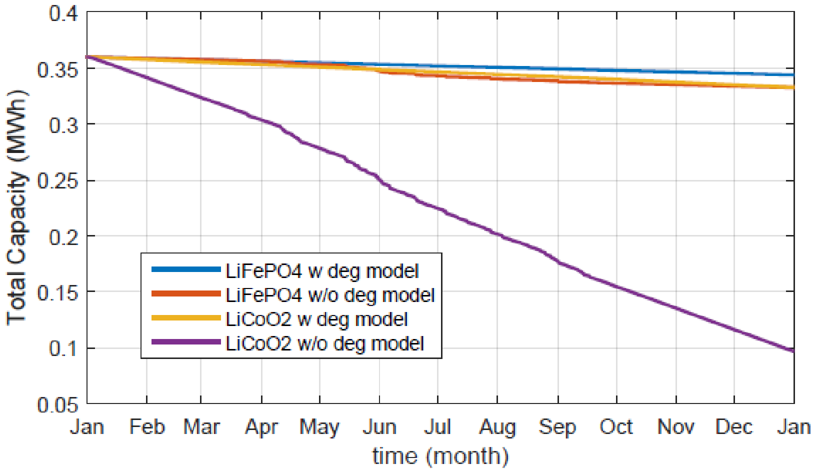
Absorb PV energy due to grid constraints

CC/CV charging



Degradation results

- Capacity fade for two different battery technologies for 1 year



- LiCoO2 system is very sensitive to low SOC regimes

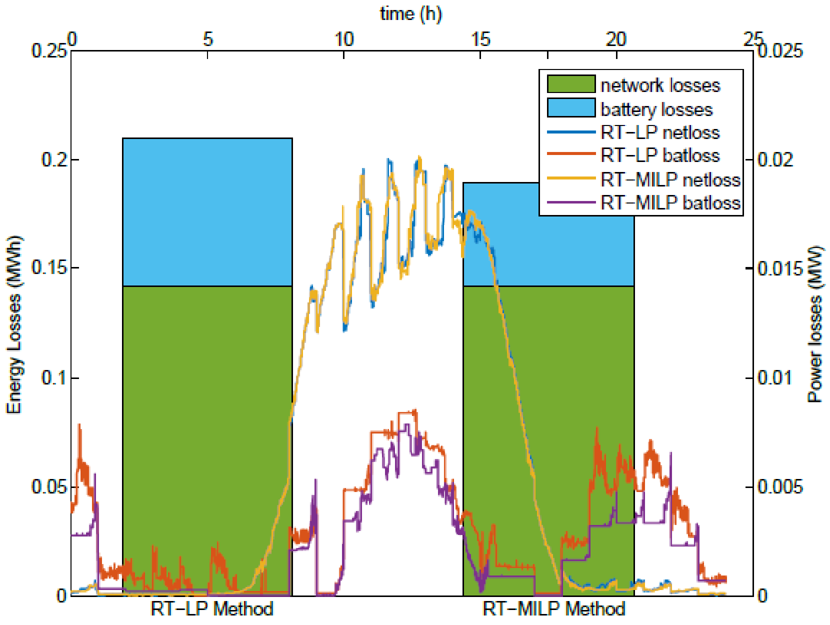
- Life Cycle Assessment

Battery Technology	**Deg Model**	**Expected full cycle achievement**	**Expected Lifetime (years)**
LiFePO4 [6]	yes	2816	4.4
	no	1609	2.64
LiCoO2 [14]	yes	1652	2.63
	no	166	0.29

- Including a deg model in the controllers can extend the battery lifetime by at least factor 2

RT control results

- Energy and power losses for two different controller configurations



- Loss Comparison

Controller Mode	Detailed battery model	Network losses	Battery losses
RT-MILP	Yes	141.8 kWh	47.5 kWh
RT-LP	No	141.2 kWh	68.4 kWh

- MILP saves up to 30% battery losses
- Battery losses constitute1/3 of network losses
    - Batteries could be used to reduce total losses

Conclusion battery operation

- Division of planning domain and real-time control is crucial, since they act on different time scales
- Enhanced battery models are needed for real-time control
- We can save substantially battery system losses if we consider a switched battery operation
- Consideration of degradation models is important to prolong battery lifetime
- Real-time control utilizes full grid potential by solving an RT-OPF (optimal reactive power control, optimal active power curtailment)

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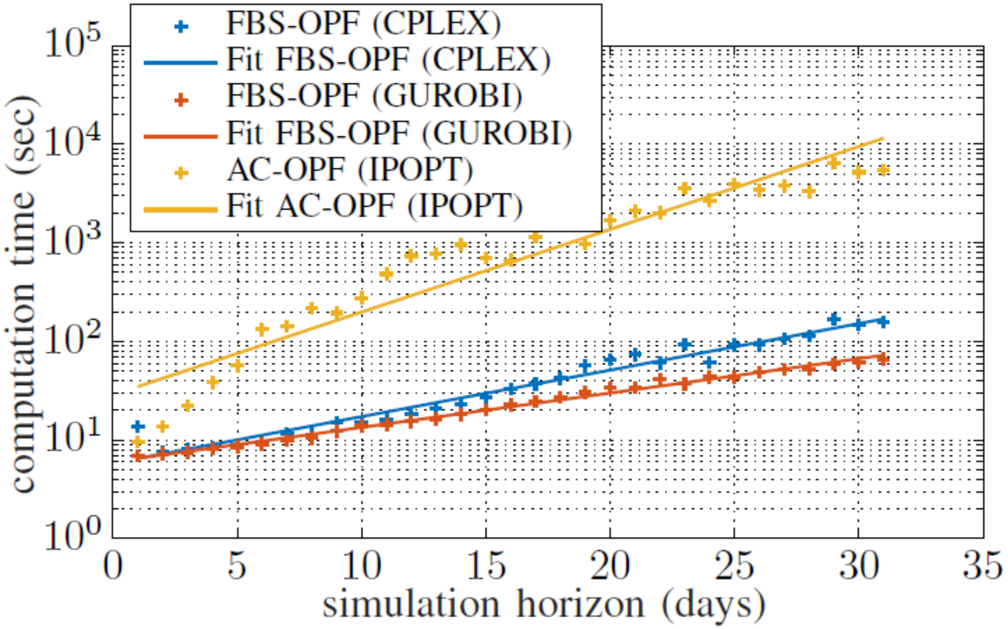
Optimal sizing and placement of storage

- Challenges
  - Link operational domain with investment planning domain (years)
  - A planning framework has to reflect the OPF strategy
  - But long planning horizons and intertemporal coupling (storage) lead to intractable planning problems

- Solution approach
  - Linearized version (FBS-OPF) of the AC-OPF can help to make the problem tractable

FBS OPF computation time



Placement of
18 storages on a 19 bus network
Resolution 1h

- Computation time grows polynomially
- FBS-OPF extrapolated 2 hours for 1 year
- AC-OPF extrapolated 27 days for 1 year (factor 300)

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Planning strategy with FBS-OPF

- **Problem Structure**

Operational strategy investments

$$\min_{\boldsymbol{X},\boldsymbol{z},\boldsymbol{l}} \left(\left(\sum_{k=0}^{N} \boldsymbol{f}^{con}(\boldsymbol{p}_{\mathrm{gen}}) \right) + \boldsymbol{f}_{s}(\boldsymbol{z}) + \boldsymbol{f}_{l}(\boldsymbol{l}) \right)$$

s.t.

Grid constraints

$$\tilde{\boldsymbol{A}}_{\mathrm{in}} \begin{bmatrix} X \\ l \end{bmatrix} \leq \tilde{\boldsymbol{b}}_{\mathrm{in}}$$

voltage and thermal limits

$$\tilde{\boldsymbol{A}}_{\mathrm{eq}} \begin{bmatrix} X \\ l \end{bmatrix} = \tilde{\boldsymbol{b}}_{\mathrm{eq}}$$

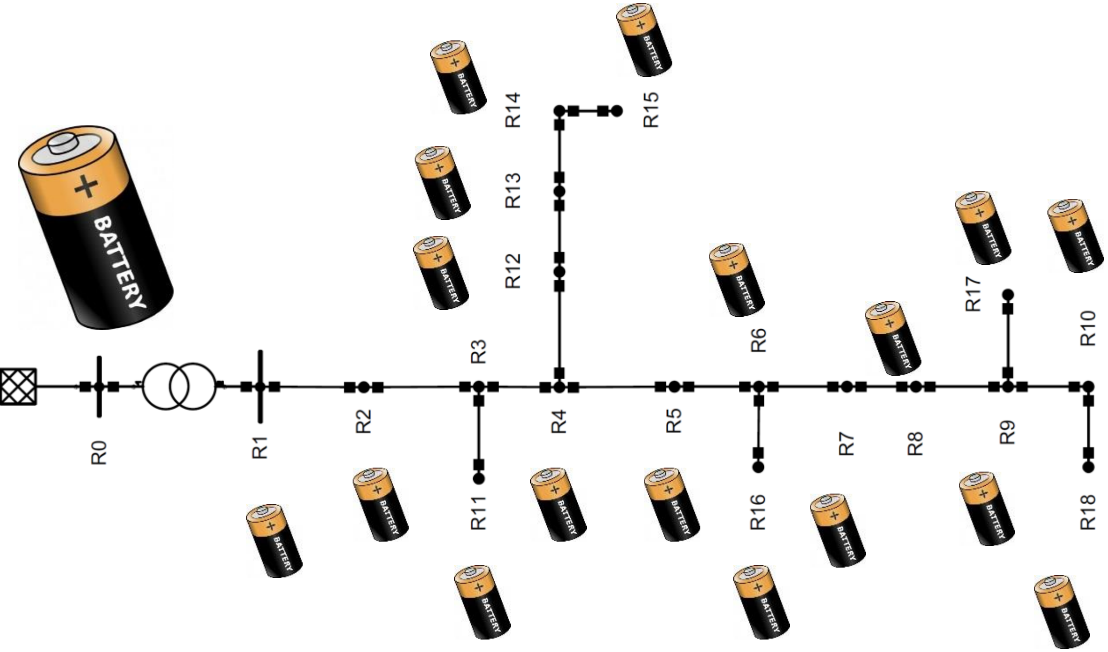
Storage coupling

$$\boldsymbol{A}_{\mathrm{s}} \begin{bmatrix} X \\ Z \end{bmatrix} \leq \boldsymbol{b}_{\mathrm{s}} \, .$$

- **Cost curves**
- Operational cost curves
  - Any convex $\boldsymbol{f}^{con}(\boldsymbol{p}_{\mathrm{gen}})$ e.g. energy prices or tariff schemes with feed-in tariff
- *Non-scalable* components
  - $\boldsymbol{f}_{l}(\boldsymbol{l})$ general integer
  - MILP problem
- *scalable* components (storage) $\boldsymbol{f}_{s}(\boldsymbol{z}) = \boldsymbol{c}_{\mathrm{S}}^{T}\boldsymbol{z}$ where $\boldsymbol{c}_{\mathrm{S}}^{T}$ is storage price

Case Study Distributed vs Centralized Storage

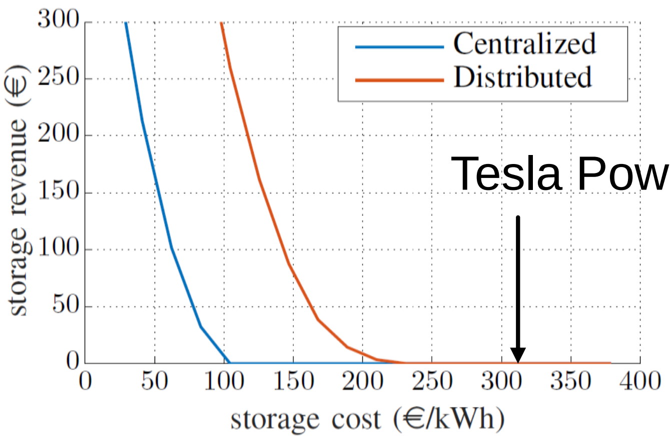
Which configuration is better, when DSO can additionally buy energy from/ sell to the market?



Storage Configuration	Centralized	Distributed
Storages	1	18
Storage Power	180kVA	10kVA
PV share	100% (19)	
PV power	30kVA	
Storage Price	25 - 300 €/kWh	
Storage Efficiency (round trip)	0.8	
Simulation Horizon	31 days	
Time Steps	744 @ 1h	
Busses	19	
Energy Price profile	EEX spotmarket	
Available PV Energy	147.13 MWh	
Consumed energy	4.84 MWh	
Households	18	

Case study results

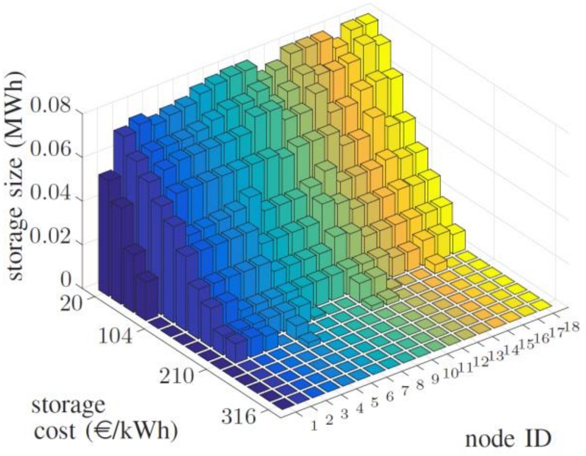
- Storage revenue for centralized and decentralized scenario

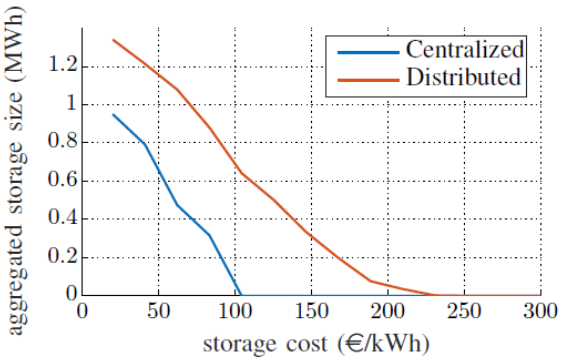


Tesla Power Wall

- Distributed scenario more profitable due to avoided PV curtailment

- Storage placement and sizing





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Conclusion planning and outlook

- We can use FBS – OPF into a planning framework to reflect a multiperiod OPF strategy (e.g. storage management, optimal APC, optimal RPC)
- AC-OPF is intractable, while FBS-OPF is tractable

- Distributed optimization due to very high RAM usage

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Conclusion and Outlook

- Intelligent battery control strategies improve economic viability of battery investments in combination with
    - detailed battery models
    - degradation models
    - Optimal Power Flow (OPF)
- Linearized OPF methods need to be considered to solve tractable planning problems
- Case studies for bigger networks reflecting different configurations (remote, rural, urban)

Thank you for your attention…

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[1] S. Schoenung, “Energy storage systems cost update,” Sandia National Laboratories, Tech. Rep. SAND2011-2730, 2011.
[2] P. Poonpun and W. Jewell, “Analysis of the cost per kilowatt hour to store electricity,” Energy Conversion, IEEE Transactions on, vol. 23, no. 2, pp. 529–534, 2008.
[3] S. J. Moura, J. L. Stein, and H. K. Fathy, “Battery-health conscious power management in plug-in hybrid electric vehicles via electrochemical modeling and stochastic control,” Control Systems Technology, IEEE Transactions on, vol. PP, no. 99, p. 1, 2012.
[4] M. Koller, T. Borsche, A. Ulbig, and G. Andersson, “Defining a degradation cost function for optimal control of a battery energy storage system,” in PowerTech (POWERTECH), 2013 IEEE Grenoble, 2013, pp. 1–6.
[5] T. F. Fuller, M. Doyle, and J. Newman, “Simulation and optimization of the dual lithium ion insertion cell,” Journal of The Electrochemical Society, vol. 141, no. 1, pp. 1–10, 1994.
[6] M. Doyle and J. Newman, “Analysis of capacity-rate data for lithium batteries using simplified models of the discharge process,” Journal of Applied Electrochemistry, vol. 27, no. 7, pp. 846–856, 1997.
[7] E. Vrettos and S. Papathanassiou, “Operating policy and optimal sizing of a high penetration RES-BESS system for small isolated grids,” Energy Conversion, IEEE Transactions on, vol. 26, no. 3, pp. 744–756, 2011.
[8] A. Di Giorgio, L. Pimpinella, and F. Liberati, “A model predictive control approach to the load shifting problem in a household equipped with an energy storage unit,” in Control Automation (MED), 2012 20th Mediterranean Conference on, 2012, pp. 1491–1498.
[9] O. Tremblay, L.-A. Dessaint, and A.-I. Dekkiche, “A generic battery model for the dynamic simulation of hybrid electric vehicles,” in Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE, sept. 2007, pp. 284 –289.
[10] J. F. Manwell and J. G. McGowan, “Lead acid battery storage model for hybrid energy systems,” Solar Energy, vol. 50, no. 5, pp. 399 – 405, 1993.
[11] K. Heussen, S. Koch, A. Ulbig, and G. Andersson, “Energy storage in power system operation: The power nodes modeling framework,” in Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES, Oct. 2010.
[12] P. Ramadass, B. Haran, P. M. Gomadam, R. White, and B. N. Popov, “Development of first principles capacity fade model for Li-ion cells,”Journal of The Electrochemical Society, vol. 151, no. 2, pp. A196–A203, 2004.
[13] G. L. Plett, “Recursive approximate weighted total least squares estimation of battery cell total capacity,” Journal of Power Sources, vol. 196, no. 4, pp. 2319 – 2331, 2011.
[14] Forman, J. C., Moura, S. J., Stein, J. L., & Fathy, H. K. (2012). Optimal Experimental Design for Modeling Battery Degradation. *5th Annual Dynamic Systems and Control Conference Joint with the JSME 11th Motion and Vibration Conference*, *1*, 309–318. http://doi.org/10.1115/DSCC2012-MOVIC2012-8751