Dispatch and clustering of ancillary services from distributed storage

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ParisTech school of Mines

- Funded in **1783**
- 2’395 staff
    - 1’114 permanent staff including 286 research academics
    - 391 PhD students (100/y), 890 Master and post-master students
- 18 research centers
- EUR 30 million per year contractual research budget (ARMINES)
- **1st** engineering school in France for contractual volume research
- 5 sites: Paris, Évry, Fontainebleau, Palaiseau, Sophia Antipolis.

ParisTech headquarter in Paris

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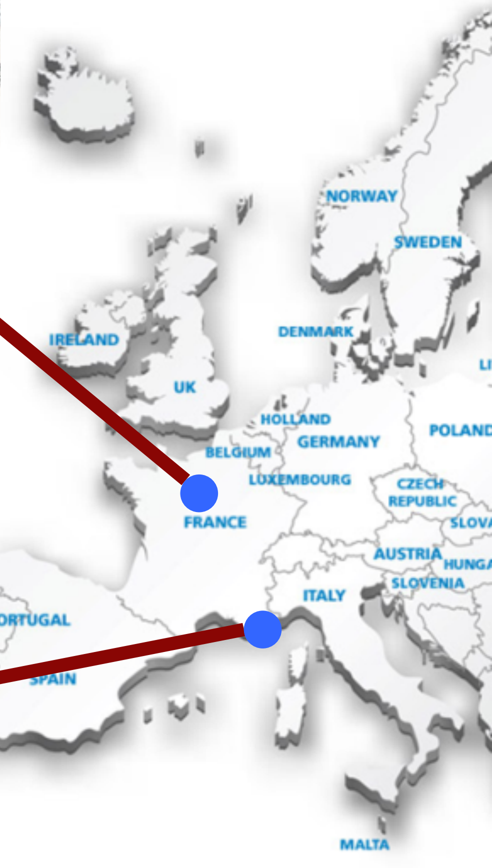


Centre for processes, renewable energies and energy systems (PERSEE) in Sophia Antipolis Nice.

Outline

1. Introduction
2. Dispatch of stochastic generation and distribution systems with batteries and downstream flexibility.
3. The benefit of dispatching stochastic power flows: a system-wise analysis.
4. An algorithmic framework to provide multiple ancillary services with one battery unit.
5. Conclusions

1

Integration of battery storage systems in electrical grids: mainstream trends

Battery storage integration in the electrical grid

Two operational perspectives for the integration of batteries in the grid:

- Improving system efficiency and social benefits, e.g. reducing reserve, meeting reliability levels, reducing costs, relieving congestions in transmission systems, reducing CO2 emissions (?)*.

- Increasing the hosting capacity of distribution networks for renewable generation (e.g. voltage control, congestion management, peak shaving).

* Storage might lead to increased CO2 levels due to displacing gas in favor of coal generation, see e.g. [Lueken and Apt, 2014], [Preskill and Callaway, 2018].

Storage applications at the system level

- Energy arbitrage: buying cheap electricity and reselling at higher price (**self-defeating scheme**).

- Reserve provision, i.e. using batteries to provide reserve capacity instead of conventional generation units.

- Primary frequency control.

Applications of storage in distribution systems

- Peak-shaving, PV self-consumption.
- Grid control, i.e. congestions management with nonconvex optimal power flow, convex relaxations, or linearized OPF.

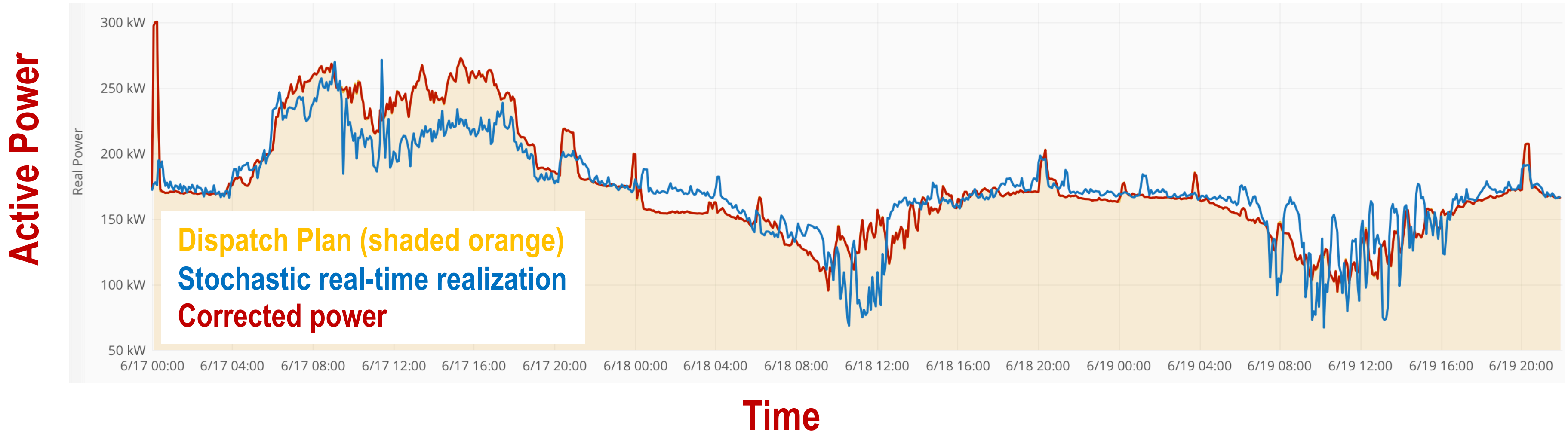
2

Dispatching stochastic generation and distribution systems with batteries and downstream flexibility

(in other words, how to seamlessly control distributed storage to help to provide services to both the local grid and the system)

Dispatching stochastic resources

- *Dispatching stochastic resources* is making sure that the aggregated active power flow of a set of heterogenous resources with stochastic output (e.g., demand + PV generation) follows a pre-established trajectory **(dispatch plan)** by controlling some flexibility.



- Relevant to reduce the need for power reserves to operate the grid (see later), as opposed to typical reserve procurement schemes (e.g., market, aggregation).

- Not totally new, e.g., proposed already for **PV plants** [Marinelli2014], [Conte et al., 2017] and **wind farms** [Abu2015].

- Extended to heterogeneous resources in [Sossan2016], [Appino2018].

Dispatching distribution systems [Sossan2016]

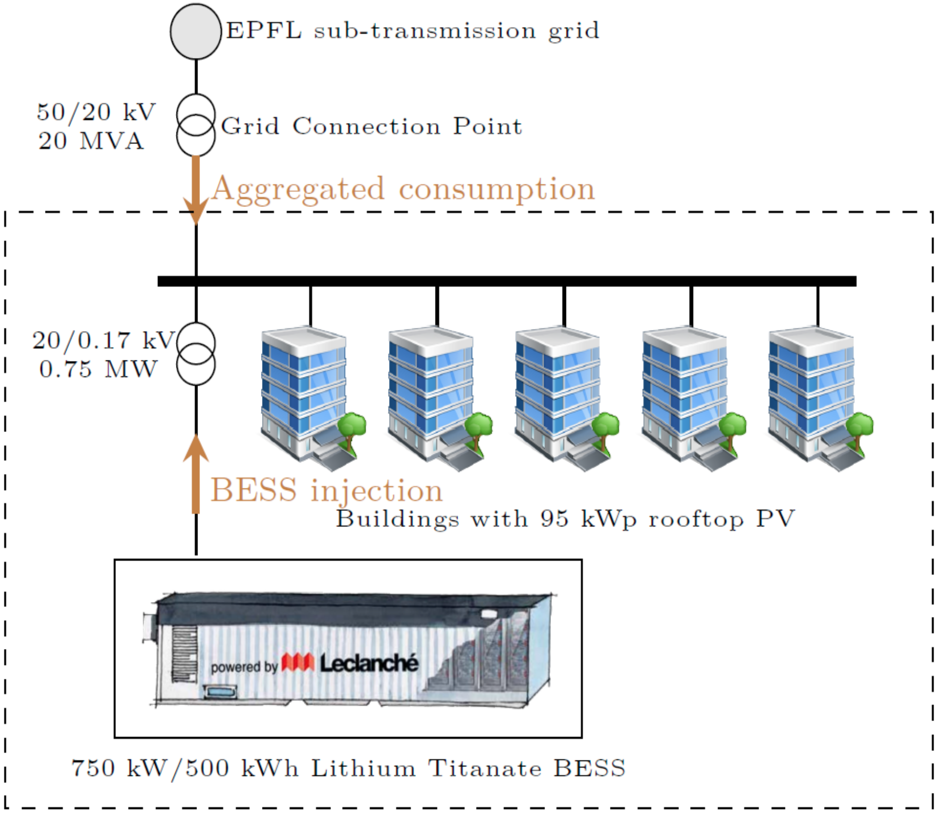


Figure: Topology of the dispatchable feeder at EPFL.

Problem Statement

1. Computing dispatch plan with given resolution, look-ahead time, and period.
2. Controlling flexibility (e.g., a grid-connected battery) in real-time to track the dispatch plan.

Definition of dispatch plan [Sossan2016]

The **dispatch plan** is a series at a certain time resolution and look-ahead horizon (say 5 minutes and 24 hours) of the scheduled active power flow at the GCP.

It is defined as:

$$\widehat{P}_t = \widehat{L}_t + F_t \qquad\qquad t = 1, \ldots, N$$

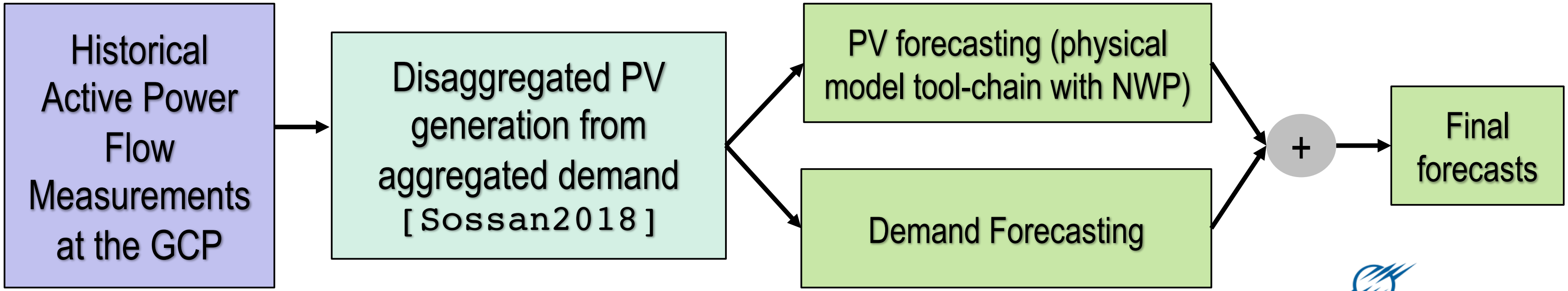
Point prediction of the prosumption at the GCP

Offset profile

It restores an adequate battery state-of-energy to ensure that enough up/down-flexibility is available during operation to compensate for the mismatch between prosumption and realization.

Dispatch plan: point predictions of the ‘prosumption’

- Forecasting stochastic demand/generation is a well-established practice. It is however challenging when at a high level of disaggregation (e.g., at low or medium voltage levels) du to high volatility and non-stationarity of the series.
- ARIMAX-class models generally fails in capturing highly disaggregated prosumption profiles.
- Non-parametric methods found to be perform better than parametric ones.
- In distribution networks with large presence of distributed PV generation, accounting for irradiance patterns is key for good performance.
- Our proposed way:

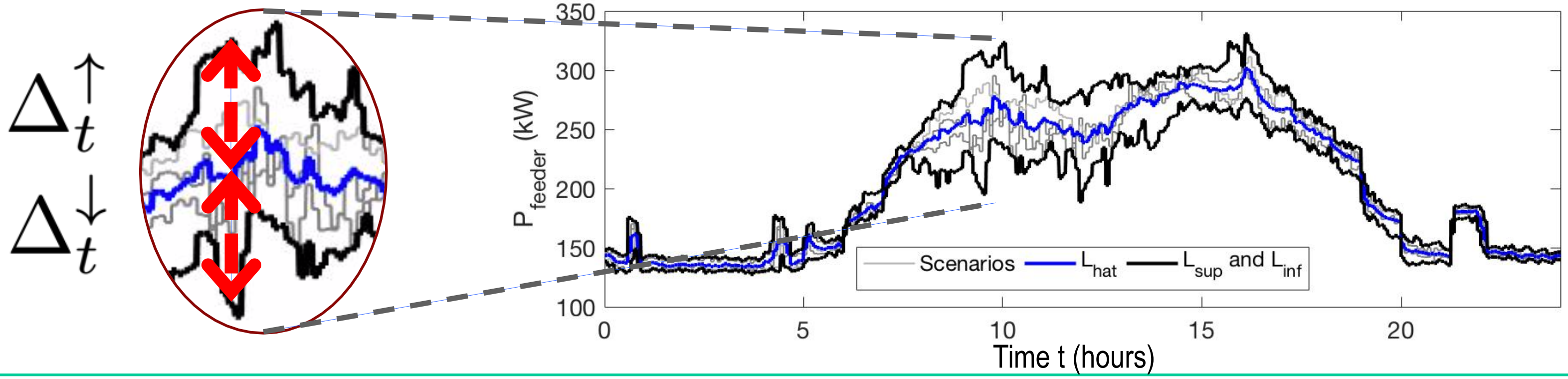


Dispatch plan: computation of the offset profile

During operation at time i, the battery compensates for the mismatch between dispatch plan $\widehat{P}_t$ and stochastic realization L_t . The battery injection is:

$$B_t = \widehat{P}_t - L_t \quad \text{by applying the dispatch plan definition} \quad B_t = F_t + \widehat{L}_t - L_t$$

Let $\Delta_t^{\uparrow}, \; \Delta_t^{\downarrow}$ denote largest deviations between the extreme realizations of the demand and the point predictions.



Battery action in worst cases

$$B_t^{\uparrow} = F_t + \Delta_t^{\uparrow}$$

$$B_t^{\downarrow} = F_t + \Delta_t^{\downarrow}$$

Battery state-of-energy in worst case scenarios

$$\mathrm{SOE}_{t+1}^{\uparrow} = \mathrm{SOE}_t^{\uparrow} + \beta^+ \left[B_t^{\uparrow}\right]^+ + \beta^- \left[B_t^{\uparrow}\right]^-$$

$$\mathrm{SOE}_{t+1}^{\downarrow} = \mathrm{SOE}_t^{\downarrow} + \beta^+ \left[B_t^{\downarrow}\right]^+ + \beta^- \left[B_t^{\downarrow}\right]^-$$

Dispatch plan: computation of the offset profile – cont'd

With $\Delta_t^{\uparrow}$, $\Delta_t^{\downarrow}$ given, we seek an offset profile $\boldsymbol{F}=[F1, .., FN]$ so that the battery's state-of-energy and power injection are within limits:

$$\boldsymbol{F}^o = \arg\min_{\boldsymbol{F}\in\mathbb{R}^N} \left\{ \sum_{t=1}^{N} F_t^2 \right\}$$

Sequence with least norm-2 (arbitrary, it could be just a feasibility problem)

$$\text{subject to (for } t = 0, 1, \ldots, N-1) :$$

$$B_t^{\uparrow} = F_t + \Delta_t^{\uparrow}$$

$$B_t^{\downarrow} = F_t + \Delta_t^{\downarrow}$$

$$\text{SOE}_{t+1}^{\uparrow} = \text{SOE}_t^{\uparrow} + \beta^+ \left[B_t^{\uparrow}\right]^+ + \beta^- \left[B_t^{\uparrow}\right]^-$$

$$\text{SOE}_{t+1}^{\downarrow} = \text{SOE}_t^{\downarrow} + \beta^+ \left[B_t^{\downarrow}\right]^+ + \beta^- \left[B_t^{\downarrow}\right]^-$$

Worst case lowest state-of-energy must be higher than minimum allowed

$$\text{SOE}_{t+1}^{\downarrow} \geq \text{SOE}_{\text{min}},$$

$$\text{SOE}_{t+1}^{\uparrow} \leq \text{SOE}_{\text{max}}$$

$$B_t^{\uparrow} \leq B_{\text{max}}$$

$$B_t^{\downarrow} \geq B_{\text{min}}$$

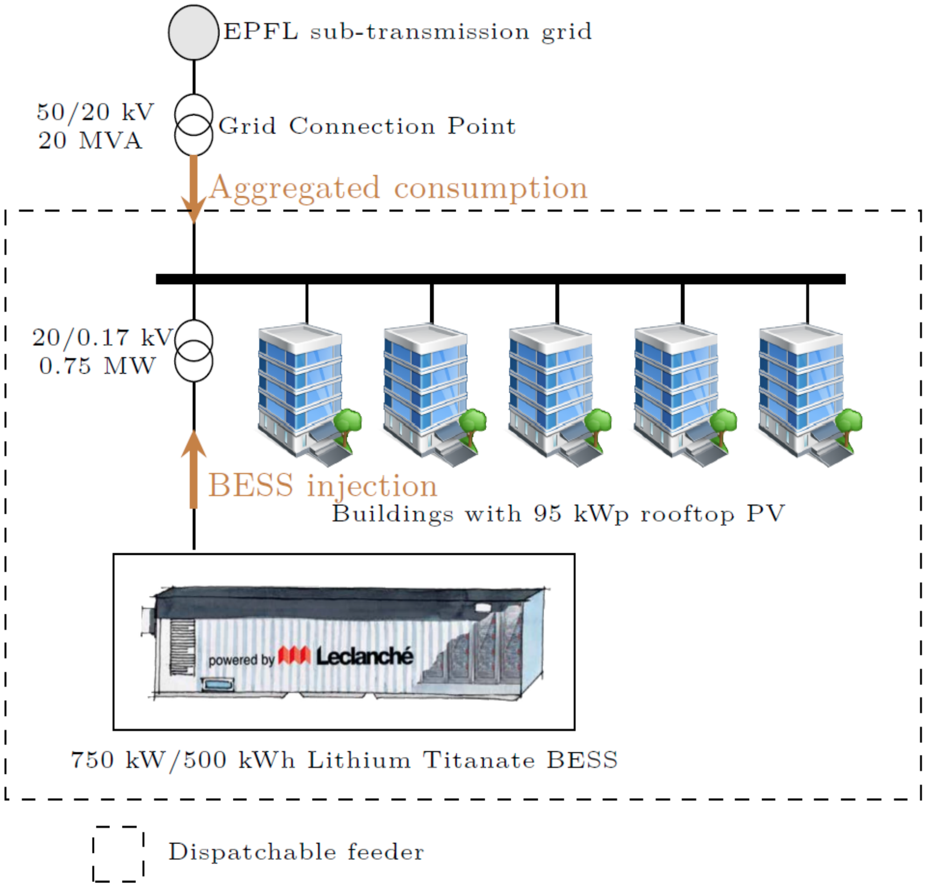
Battery's injection within converter's limit

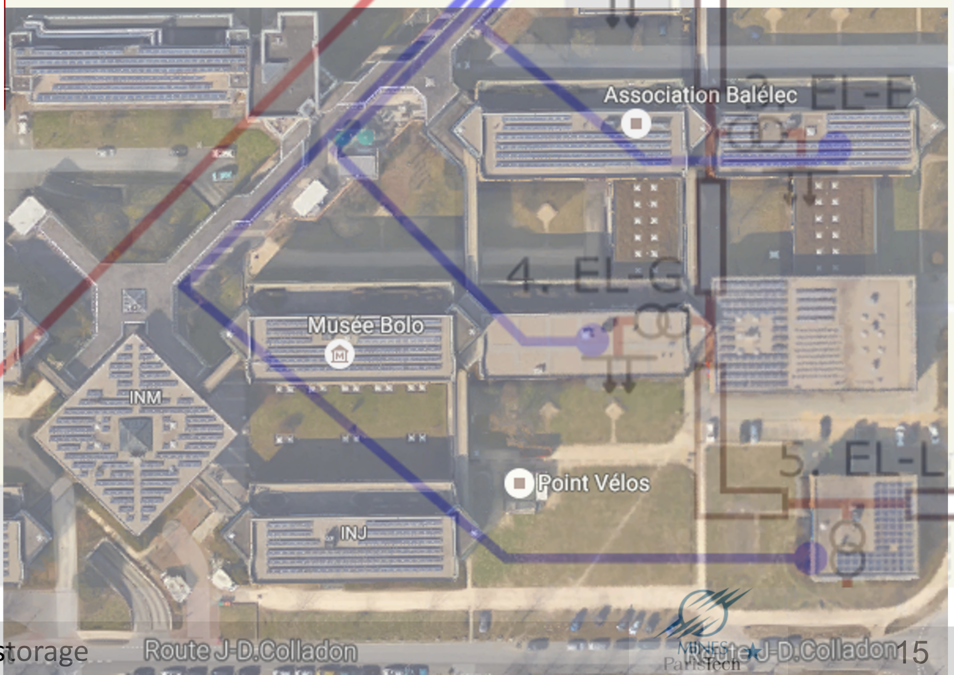
$$\widehat{P}_t \leq P_{\text{max}}$$

Flow constraint at the GCP (assuming 1 pf)

(nonconvex due to the sign operators, can be convexified as done in the paper)

Validation: experimental setup



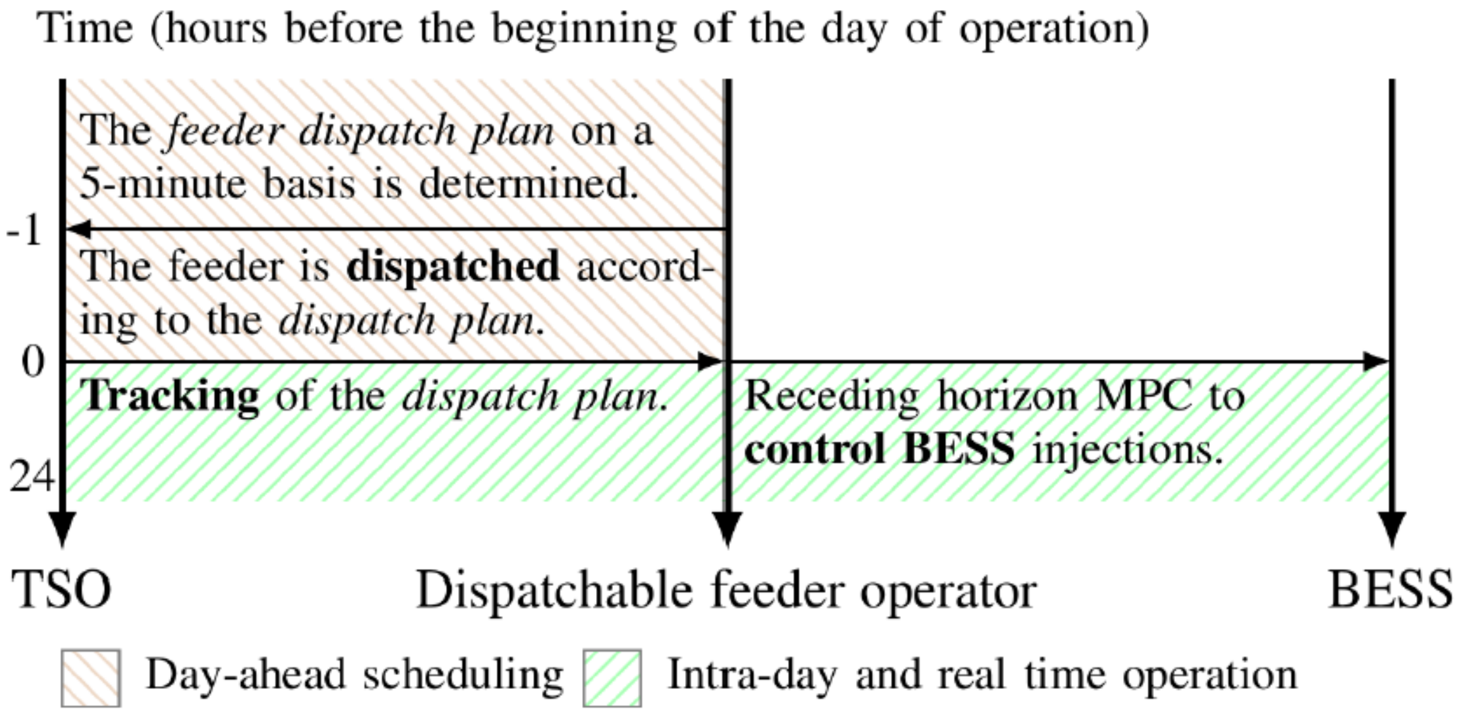


- Single measurement point at the GCP.
- 350 kW peak demand during winter.
- 95 kWp roof-top PV installation.

Validation: battery energy storage system

Parameter	Value
Nominal Capacity	720 kVA/560 kWh
GCP Voltage	20 kV
DC Bus Voltage Range	600/800 V
Cell Technology (Anode/Cathode)	Lithium Titanate Oxide (LTO) Nichel Cobalt Alumnium Oxide (NCA)
Number of racks	9 in parallel
Number of modules per rack	15 in series
Cells configuration per module	20s3p
Total number of cells	8100
Cell nominal voltage	2.3 V (limits 1.7 to 2.7 V)
Cell nominal capacity	30 Ah (69 Wh)
Round-trip efficiency (AC side)	94-96%
Round-trip efficiency (DC side)	97-99%

Validation: implementation and operation



Time (hours before the beginning of the day of operation)

The *feeder dispatch plan* on a 5-minute basis is determined.

The feeder is **dispatched** according to the *dispatch plan*.

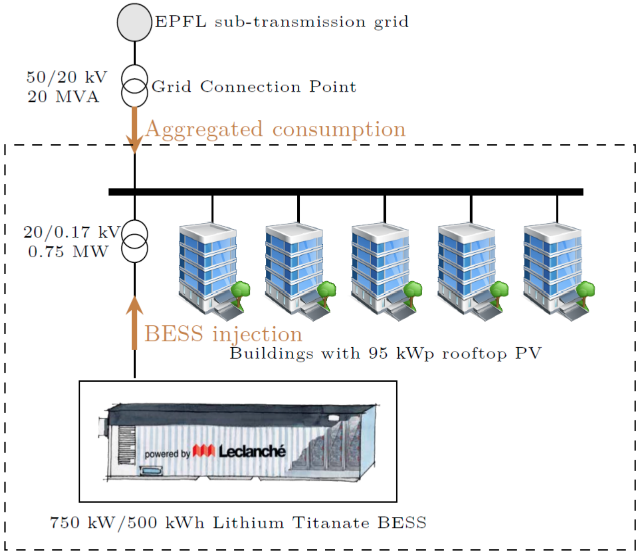
Tracking of the *dispatch plan*.

Receding horizon MPC to **control BESS** injections.

▨ Day-ahead scheduling ▨ Intra-day and real time operation

Validation: experimental results

- Dispatch on Jan 14, 2016
  https://snapshot.raintank.io/dashboard/snapshot/PuW1Rf5d470Q0gsT7UNponM25bGDNTRA
- Dispatch on Jan 13, 2016
  https://snapshot.raintank.io/dashboard/snapshot/cDS4IDniZjRiePXvusnmQXOmMwpGLnR6
- Dispatch with peak-shaving on Jun 22, 2016
  https://snapshot.raintank.io/dashboard/snapshot/LSF3bPxtWYDjHVu6siEr1VPb92EXNkd6
- Dispatch with load levelling on Mar 14, 2016
  https://snapshot.raintank.io/dashboard/snapshot/4ztn800czpAzEFRzbGOmWc1A2pKeC9ab
- Dispatch from Jun 16 to 19, 2016
  https://snapshot.raintank.io/dashboard/snapshot/TNbEgP7j1AWhaW7cEK1ZiK3tY1Or7P4U



Extension to multiple controllable resources

What if we have multiple flexible elements in the mix (e.g. battery, flexible demand and curtailable renewable generation)**?**

They all concur in achieving the dispatch control problem. In brief, the formulation can be extended by:

- Compute one dispatch plan per each element in the mix [Fabietti et al., 2018].
- The dispatch plan at the GCP is the algebraic sum of the individuals dispatch plans (eventually with losses, see [Stai, et al., 2018]).
- The real-time control problem with multiple controllable elements is distributable (tractable) [Fabietti et al., 2017] [Gupta et al., 2018].

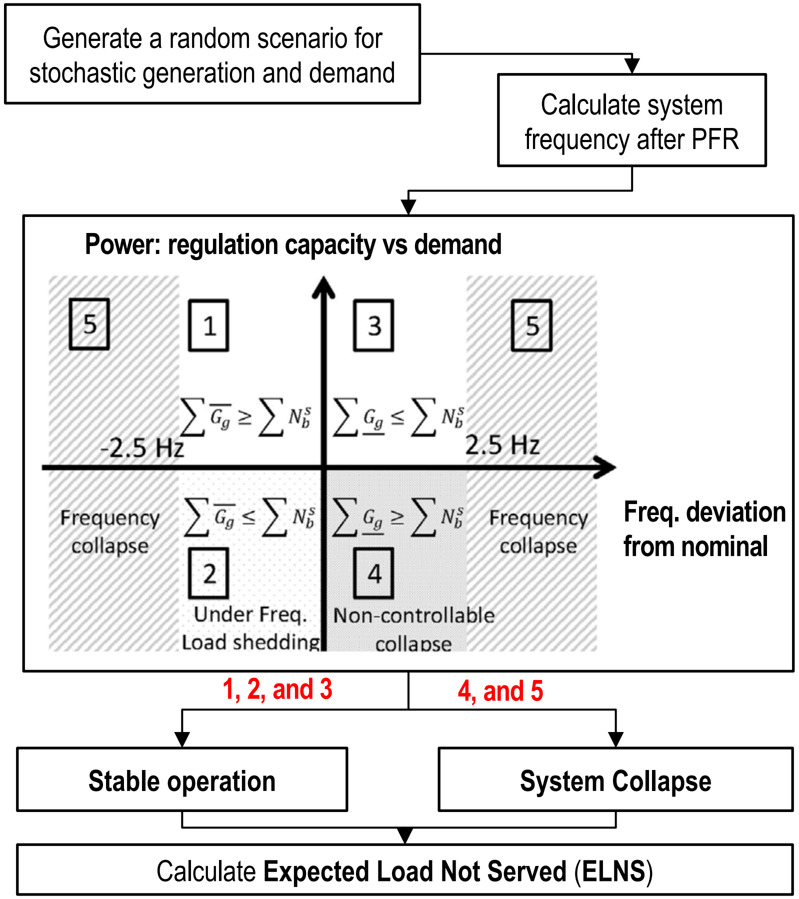
3

The benefit of dispatching stochastic power flows: a system-wise analysis

System validation [Bozorg2018]

What if dispatching distribution systems is applied as a mechanism to achieve implicit coordination between load balance responsible and aggregators?

A Monte Carlo simulation framework to simulate reserve activation as a function of the grid frequency and load shedding.



Generate a random scenario for stochastic generation and demand

Calculate system frequency after PFR

Power: regulation capacity vs demand

Freq. deviation from nominal

1, 2, and 3

4, and 5

Stable operation

System Collapse

Calculate **Expected Load Not Served** (**ELNS**)

We measure the impact of dispatching vs non-dispatching by measuring the amount of **energy not served** in a large power system.

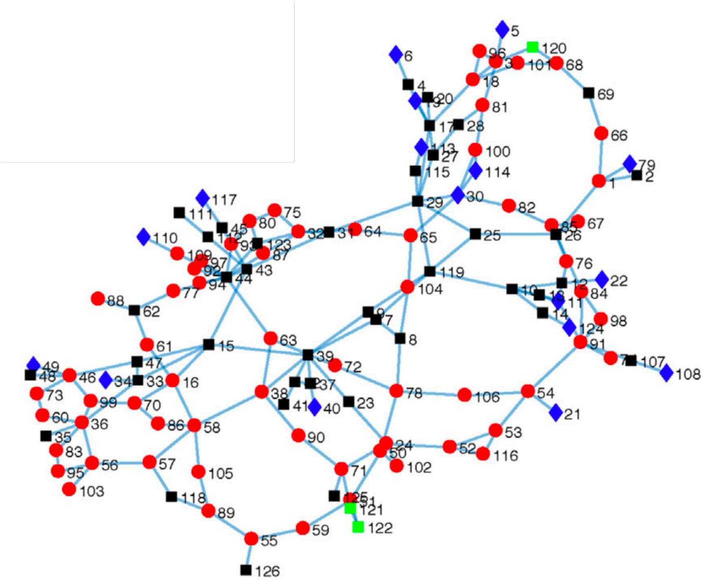


Figure. Case study:126-bus Western Danish transmission system (400, 165 kV).

System validation [Bozorg2018]

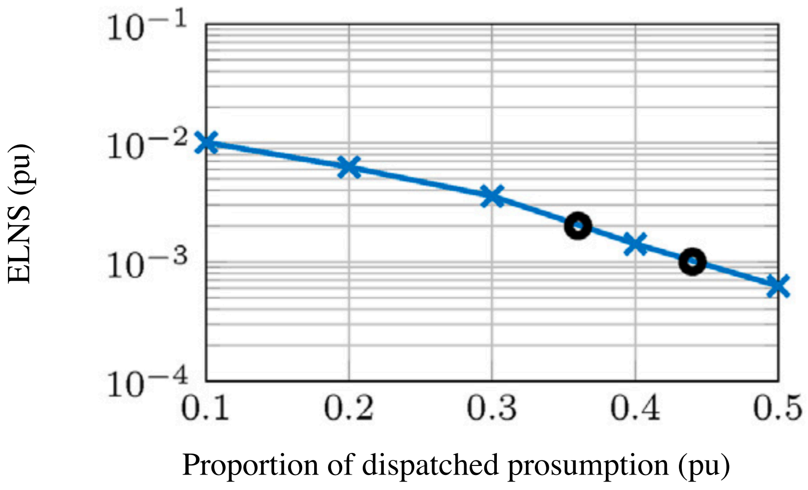


Fig.: Energy not served vs proportion of dispatched prosumption → **increasing dispatch improves reliability.**

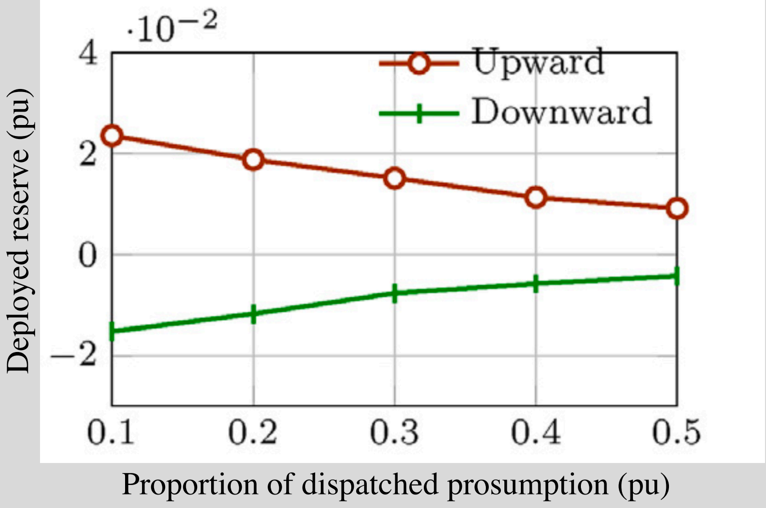


Fig.: Deployed power reserves vs penetration of dispatchable feeders at constant energy reserve.

We use a model from the literature to assess the cost of the regulating and calculate the economic pay-back time.

(*) Skytte, K., 'An econometric analysis for the regulating power market', 1999.

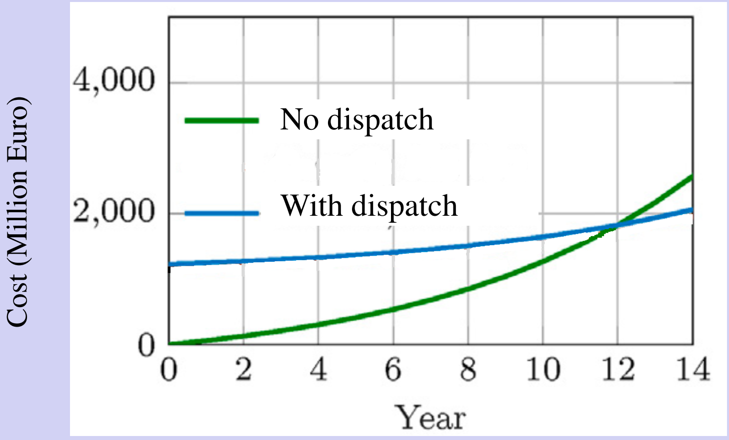


Fig.: Operational costs and pay-back time at .5 dispatched presumption → **pay-back time is compatible with storage life-time**.

4

An algorithmic framework to provide multiple ancillary services with one battery unit

Provision of multiple ancillary services [Namor2018]

Single-service applications might underuse battery's power rating and energy capacity:

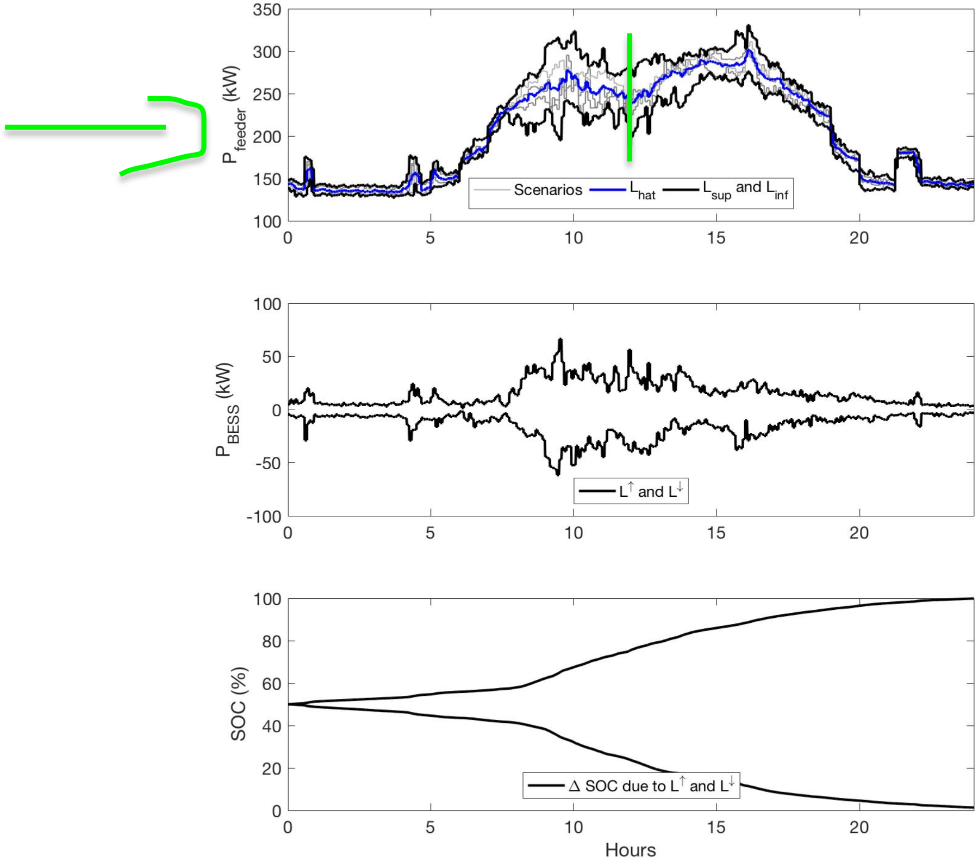


Fig.: Dispatch with **high** uncertainty.

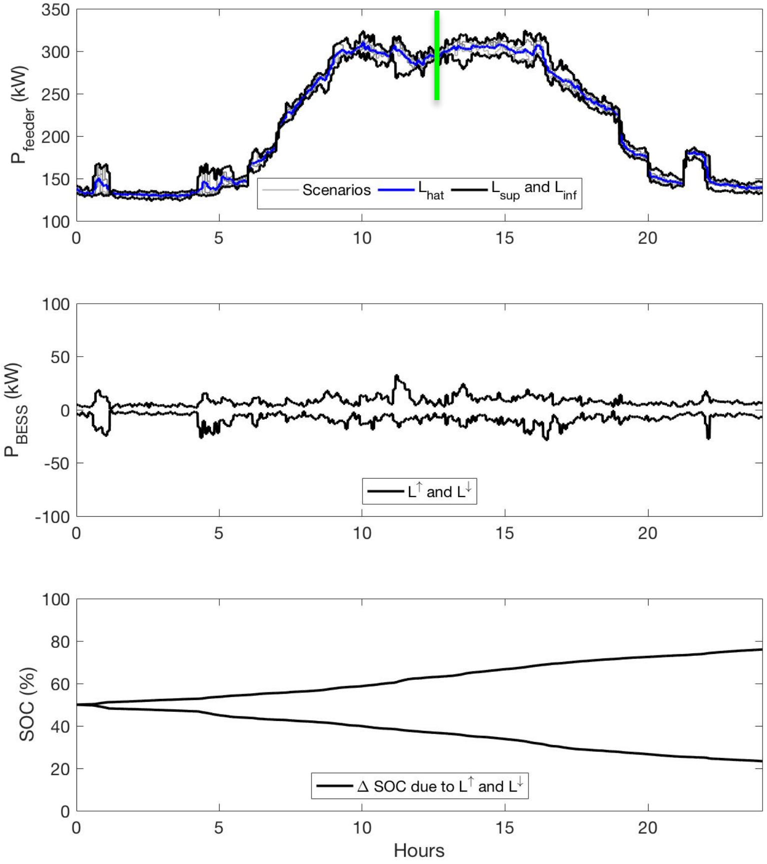
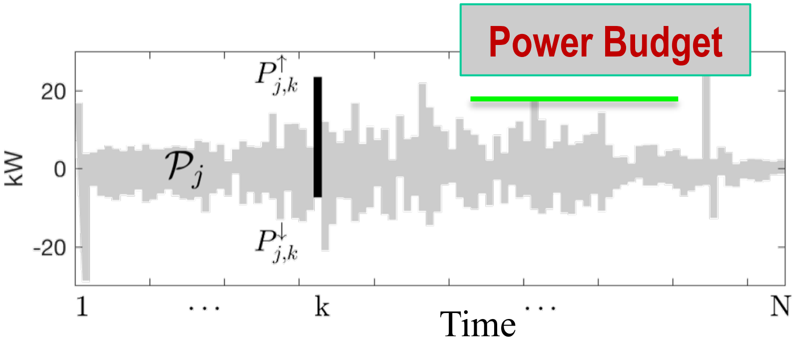


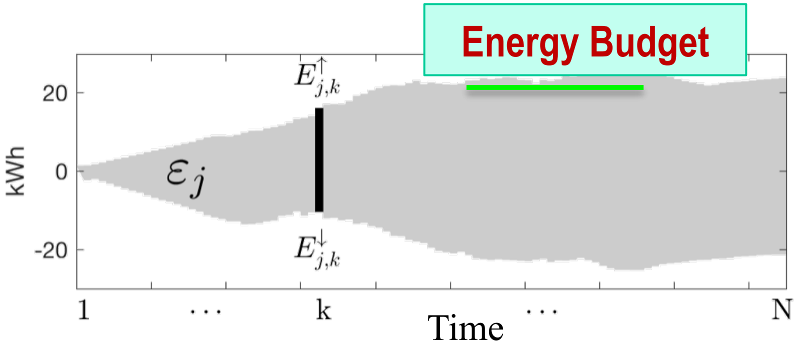
Fig.: Dispatch with **low** uncertainty.

Residual power/energy capacity can be used to **provide multiple ancillary services simultaneously**.

Algorithm for stacking ancillary services

We have multiple services to provide. We define for each grid ancillary service j the:





$$\mathcal{P}_j = \left\{ \left[P^{\downarrow}_{j,k}(x,\theta), P^{\uparrow}_{j,k}(x,\theta) \right], k = 1, \dots, N \right\}$$

$$\mathcal{E}_j = \left\{ \left[E^{\downarrow}_{j,k}(x,\theta), E^{\uparrow}_{j,k}(x,\theta) \right], k = 1, \dots, N \right\}$$

parametrized over vector of controller's parameters x and forecast of the unitary budgets θ.

Operator to determine width of envelopes: $w(\mathcal{E}_j(x,\theta)) \triangleq \{E^{\uparrow}_{j,k}(x,\theta) - E^{\downarrow}_{j,k}(x,\theta), k = 1, \dots, N\}$

We seek to find the controllers' parameters which maximize the exploitation of the battery energy capacity subject to the battery's power and energy constraints.

$$\arg\max_{x} \left\| w\Big(\sum_j \mathcal{E}_j(x,\theta)\Big) \right\|_1$$

subject to:

$$E_{init} + \sum_j \mathcal{E}_j(x,\theta) \in [E_{min}, E_{max}]$$

$$\sum_j \mathcal{P}_j(x,\theta) \in [-P_{max}, P_{max}]$$

Stacking ancillary services: Results

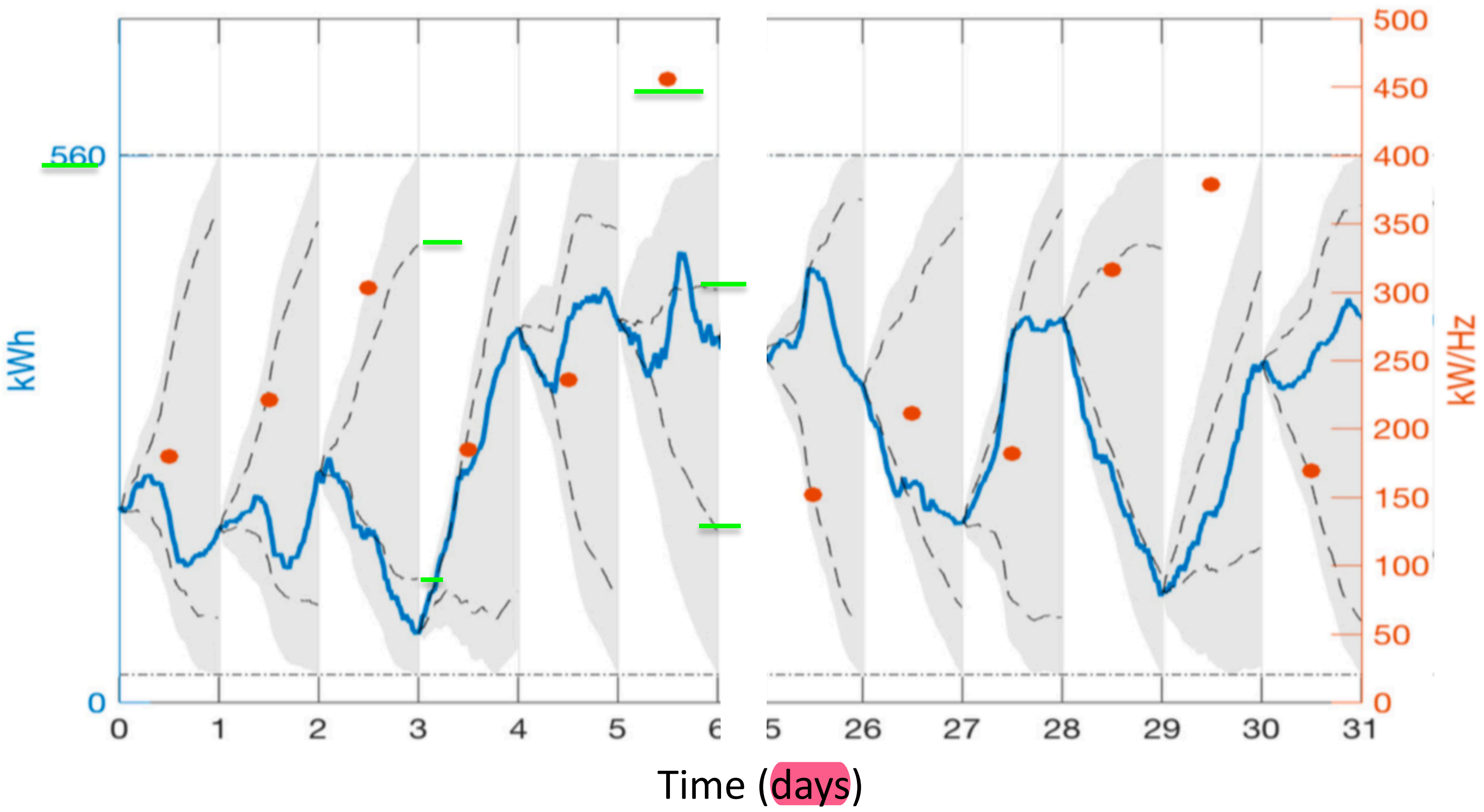
Dispatch + primary frequency regulation (PFR)

	Dispatch	PFR
Power Budget	Worst case high and worst case low power deviation from the dispatch plan.	Drop coefficient (**unknown, to determine**) time worst case frequency deviation (200 mHz).
Energy Budget	Integral of worst case deviations.	5-95% quantiles of the distribution of the accumulated frequency deviation in 1 day over a 2-year period.

Link to results

Stacking ancillary services: Results

Day-ahead scheduling for dispatch and primary frequency control



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Energy limits

Link to results

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Energy allocated for dispatch

●

Allocated droop coefficient (one per day)

▬

Total allocated energy

Conclusions

- Dispatching stochastic prosumption by using downstream flexibility achieves to reduce reserve requirements.
- Cost effective: pay-back time is shorter than storage life.
- It can be regarded to as a way to achieve efficient coordination between DSOs and load balance responsible.
- We outlined an algorithmic framework to provide multiple ancillary services with the same battery.

References

Thanks for your attention!

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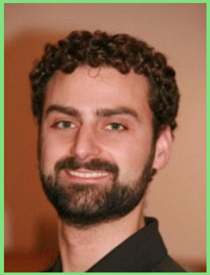
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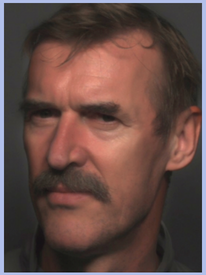
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