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Achieving the Dispatchability of Stochastic Power Flows by Distributed Control of Dispersed Energy Resources

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Question time

From a power system operation technical perspective, which are the pressing concerns related to renewable generation?

1. Availability
2. Predictability
3. Intermittency

Question time!

From a power system operation technical perspective, which are the pressing concerns related to renewable generation?

1. ~~Availability~~
2. **Predictability**
3. Intermittency

Predictability

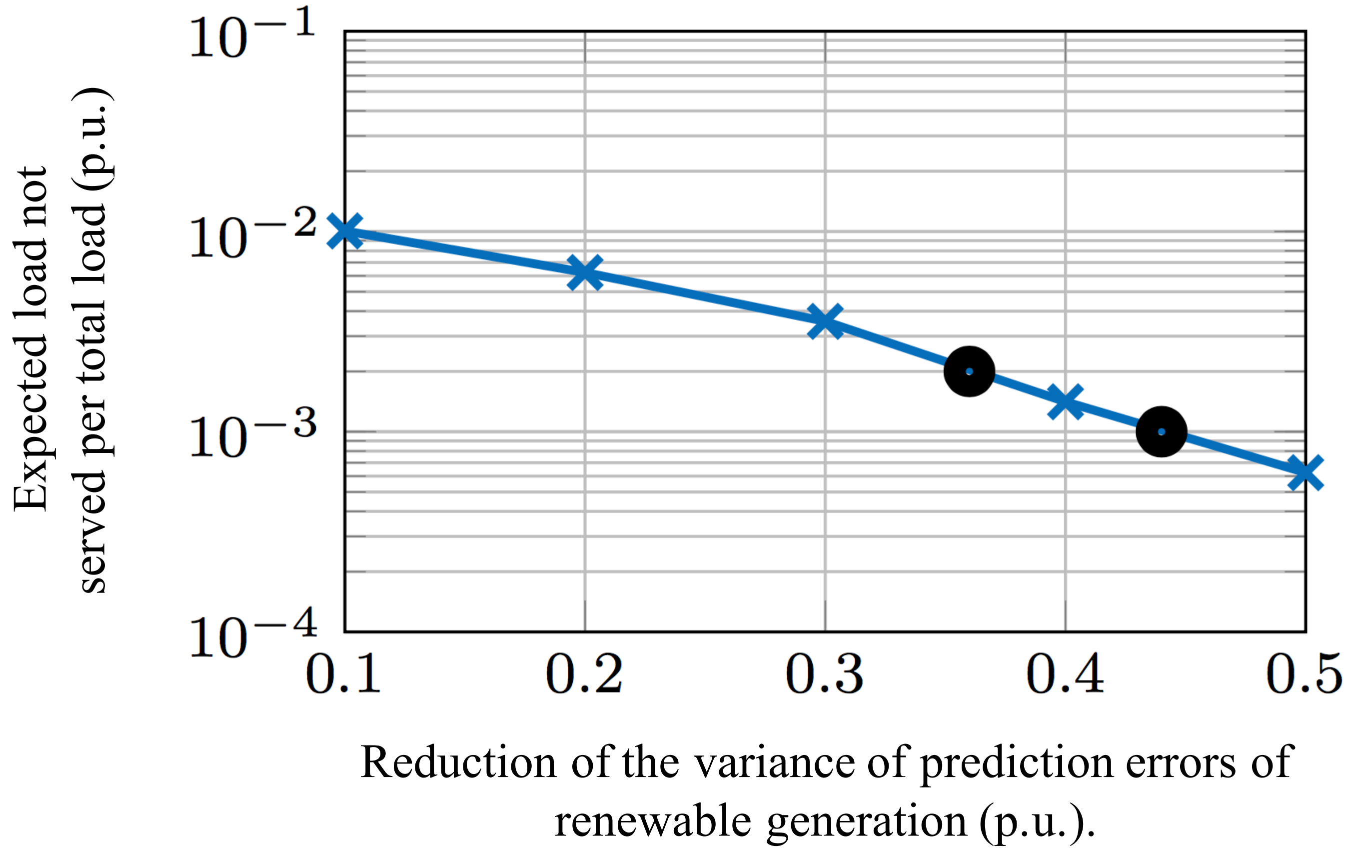


Fig.: Reliability vs reduction in forecast uncertainty.

(Adapted from M. Bozorg et al. Evaluation of the impact of dispatched-by-design operation on power system reserve requirements. Submitted to IEEE Transactions on Power Systems, 2017)

Intermittency

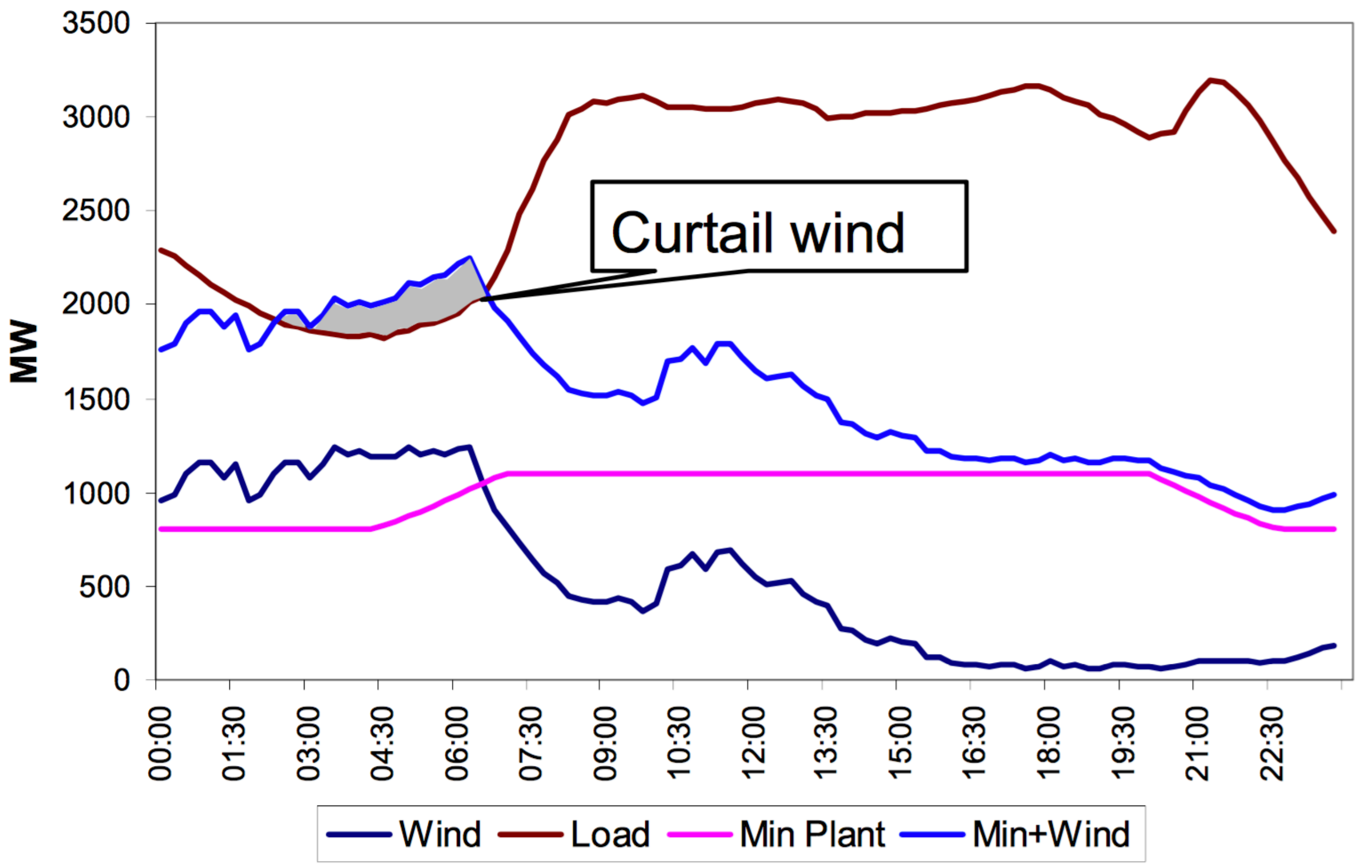
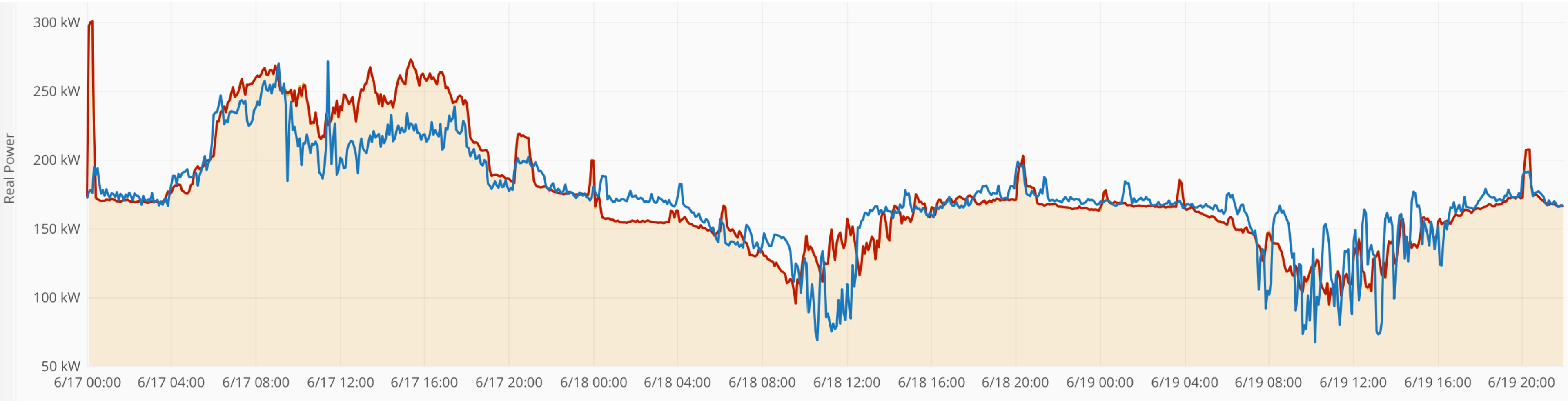


Fig.: Wind generation curtailment policy in EirGrid power system.

(I.M. Dudurych. On-line assessment of secure level of wind on the Irish power system. Proceedings of IEEE PES GM, 2010)

Objective of this research

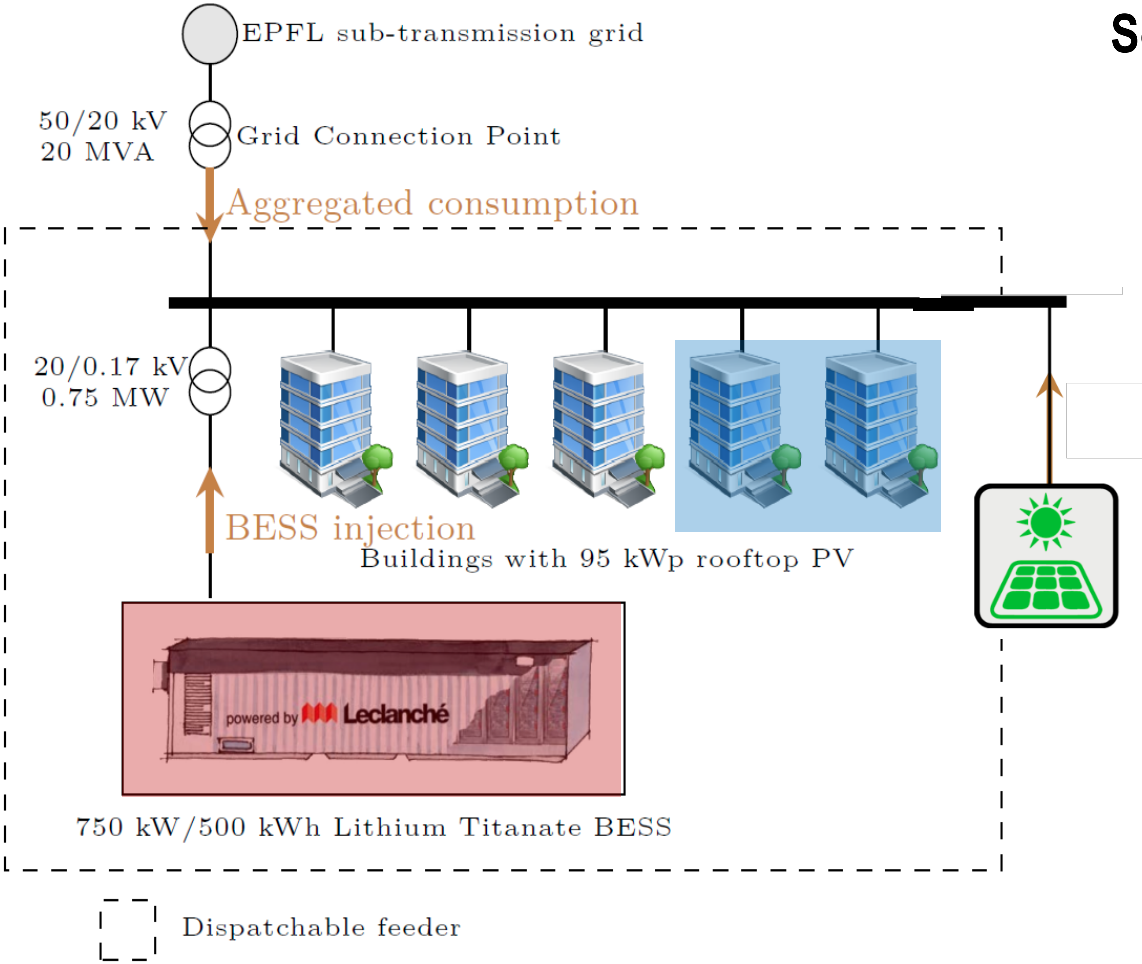
To tackle the challenge of predictability and intermittency, we propose to use local storage to dispatch the operation of stochastic power flows by tapping local flexibility.



Dispatch Plan (shaded yellow)   Stochastic slow   Corrected stochastic flow

Challenges: Complexity due to large number of units (scalable setup), possibly few measurements points.

The topology of a dispatchable feeder

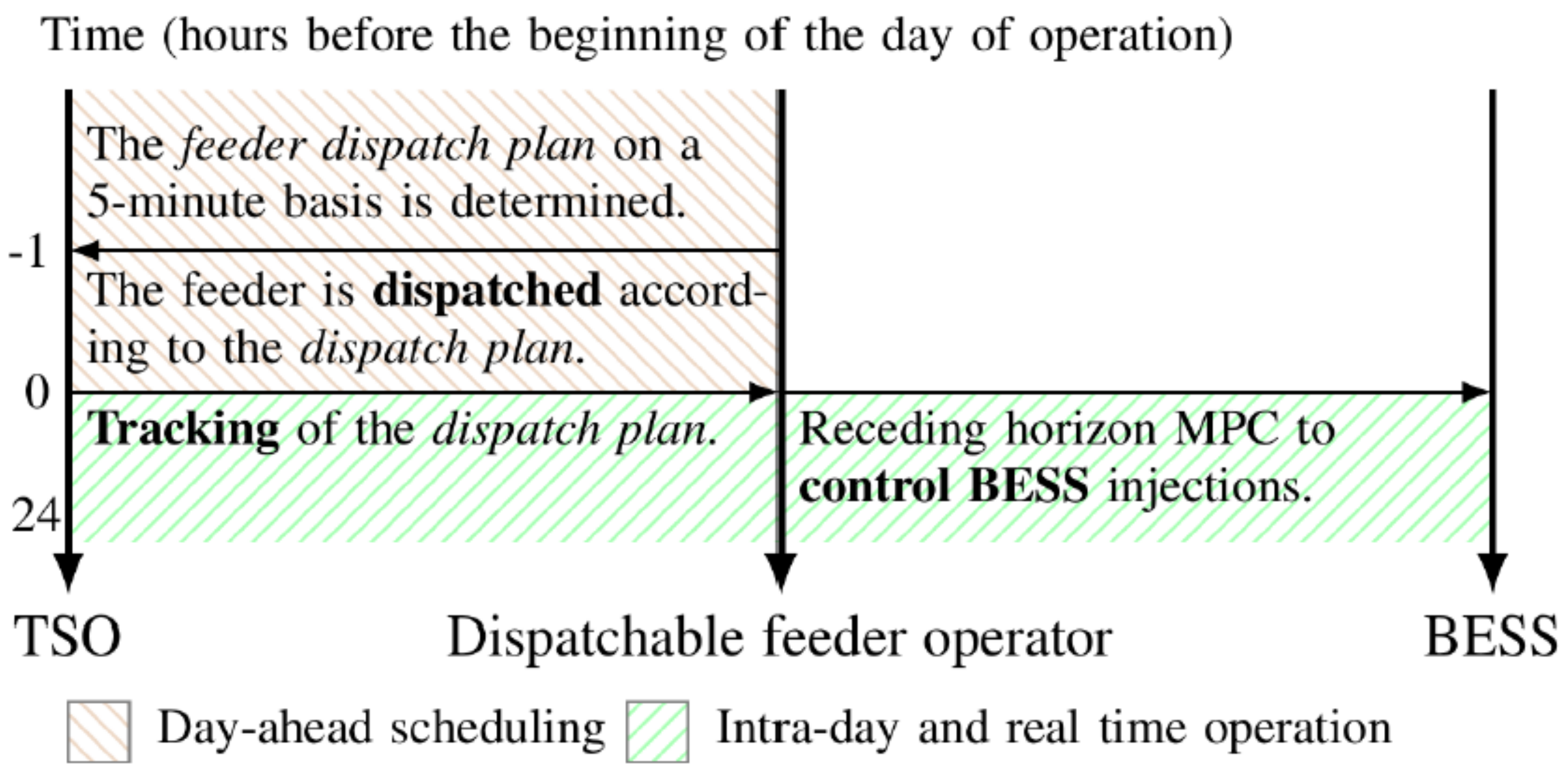


Sources of flexibility:

- Physical energy storage storage systems
- Flexible Demand (space heating)
- Curtailable PV facility

The operation of a group of stochastic prosumers (**generation + demand**) is dispatched according to a profile established the day before operation (called **dispatch plan**) by controlling flexible resources.

Formulation – A two stage process



(Fabrizio Sossan, Emil Namor, Rachid Cherkaoui, and Mario Paolone. Achieving the dispatchability of distribution feeders through prosumers data driven forecasting and model predictive control of electrochemical storage. IEEE Transactions on Sustainable Energy, 7(4):1762–1777, Oct 2016)

Formulation – Day-ahead planning

The **dispatch plan** is a sequence at 5 minute resolution that denotes the power flow at the grid connection point that the feeder should follow.

It is the **sum between prosumption point predictions and the so-called offset profile**:

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

The latter is with the objective of **restoring an adequate battery state-of-energy** such that, during operation, enough up/down-flexibility is available to compensate the mismatch between presumption and realization.

Formulation – Day-ahead: Prosumption point predictions

The problem is forecasting the prosumption for the next 24 hours period based on historical observations.

1. Historical data are **disaggregated** into {*demand, PV generation*} by using an unsupervised algorithm[1].

2. Disaggregated profiles are forecasted by **applying**:
   - **Vector auto-regression** for demand.
   - PV generation by using **a model-based tool chain** {GHI predictions, transposition model, PV model}.
3. Forecasted profiles are **aggregated back together**.
4. The outputs are point predictions and scenarios.

[1] "Unsupervised Disaggregation of PhotoVoltaic Production from Composite Power Flow Measurements of Heterogeneous Prosumers", F. Sossan, L. Nespoli, V. Medici, M. Paolone, Available on ArxiV.

Formulation – Day-ahead: Offset profile (non convex)

Provided with previous scenarios, we seek for an offset profile $\boldsymbol{F}$ such that the battery state-of-energy is within the allowed bounds for worst case scenarios $L_i^{\uparrow}, L_i^{\downarrow}$.

$$\boldsymbol{F}^o = \underset{\boldsymbol{F}\in\mathbb{R}^N}{\arg\min} \left\{ \sum_{i=1}^{N} F_i^2 \right\}$$

$$\begin{aligned}
&\text{subject to} \\
&\quad \text{SOE}_{i+1}^{\downarrow} = \text{SOE}_i^{\downarrow} + \beta^+ \left[F_i^o + L_i^{\downarrow}\right]^+ + \beta^- \left[F_i^o + L_i^{\downarrow}\right]^- \\
&\quad \text{SOE}_{i+1}^{\uparrow} = \text{SOE}_i^{\uparrow} + \beta^+ \left[F_i^o + L_i^{\uparrow}\right]^+ + \beta^- \left[F_i^o + L_i^{\uparrow}\right]^- \\
&\quad \text{SOE}_{i+1}^{\downarrow} \geq \text{SOE}_{\text{min}}, \\
&\quad \text{SOE}_{i+1}^{\uparrow} \leq \text{SOE}_{\text{max}} \\
&\quad F_i + L_i^{\downarrow} \geq B_{\text{min}} \\
&\quad F_i + L_i^{\uparrow} \leq B_{\text{max}} \\
&\quad \widehat{P}_i \leq P_{\text{max}} \\
&\text{for } i = 0, \dots, N-1
\end{aligned}$$

Note that this is a non convex problem due to the sign operators $[\cdot]^+, [\cdot]^-$.

Formulation – Day-ahead: Offset profile (convex)

The previous problem can be formulated as a convex one by **writing the sign operator as the sum of two mutually exclusive terms**. We define:

$$K_i = F_i^o + L_i^{\downarrow} = K_i^+ - K_i^-, \qquad K_i^+ \geq 0,\ K_i^- \geq 0$$
$$G_i = F_i^o + L_i^{\uparrow} = G_i^+ - G_i^-, \qquad G_i^+ \geq 0,\ G_i^- \geq 0$$

which are used to rewrite the previous optimization problem. **The cost function achieves to keep the positive and negative components mutually exclusive**.

$$\underset{\boldsymbol{K}^+,\boldsymbol{K}^-,\boldsymbol{G}^+,\boldsymbol{G}^- \in \mathbb{R}^N}{\arg\min} \left\{ \sum_{i=1}^{N} \left(K_i^+ + K_i^- + G_i^+ + G_i^- \right) \right\}$$

subject to:

$$K_i^+ - K_i^- - L_i^{\downarrow} = G_i^+ - G_i^- - L_i^{\uparrow}$$
$$\mathrm{SOE}_{i+1}^{\downarrow} = \mathrm{SOE}_i^{\downarrow} + \beta^+ K_i^+ - \beta^- K_i^-$$
$$\mathrm{SOE}_{i+1}^{\uparrow} = \mathrm{SOE}_i^{\uparrow} + \beta^+ G_i^+ - \beta^- G_i^-$$
$$\mathrm{SOE}_i^{\uparrow} \geq \mathrm{SOE}_{\min}$$
$$\mathrm{SOE}_i^{\uparrow} \leq \mathrm{SOE}_{\max}$$
$$\vdots$$
$$F_i^o = K_i^{+^o} - K_i^{-^o} - L_i^{\downarrow}$$

Formulation – The real-time control problem (MPC)

The objective is **to track the dispatch plan**. Since it consists in accomplishing a certain energy throughput, we rely on MPC rather a conventional feedback control loop to determine the current evolution while respecting BESS operational constraints. MPC is actuated at 10 sec resolution on **a 5 min shrinking horizon by plugging in short-term prosumption forecasts and open-loop predictions of the BESS operational constraints (voltage and current)**.

Two formulations are possible:

1. determining the BESS power to accomplish the energy throughput subject to BESS constraints. However, **BESS constraints are nonlinear and nonconvex.**
2. Determining the **BESS current to minimize the distance from the target energy throughput while subject to linear voltage and current constraints**. However the cost function:

$$\left(E_{\overline{k}|k}(\boldsymbol{i}_{\overline{k}|k}) - e_k\right)^2.$$

is in the form $q(r(x))$. To be convex, it requires $r(x)$ to be convex (it is) and q convex nondecreasing (it is not), thus it is nonconvex.

Formulation – The new (convex) MPC

The BESS energy throughput in the 5 minute interval is the integral over time of the product between BESS DC current, voltage and converter efficiency alpha:

$$E_{\overline{k}|k}(\cdot) = \alpha \boldsymbol{v}_{\overline{k}|k}^T \boldsymbol{i}_{\overline{k}|k}$$

The BESS voltage dynamic evolution depends on the charge/discharge current. It can be modelled by using a **three-time-contant (TTC)** model as a function of the initial BESS state x_k as the following linear relantioship.

$$\boldsymbol{v}_{\overline{k}|k} = \phi^v x_k + \psi_i^v \boldsymbol{i}_{\overline{k}|k} + \psi_1^v \mathbf{1}$$

which replaced in the first expression leads to:

$$E_{\overline{k}|k}(\cdot) = \alpha \left(x_k^T {\phi^v}^T \boldsymbol{i}_{\overline{k}|k} + \boldsymbol{i}_{\overline{k}|k}^T {\psi_i^v}^T \boldsymbol{i}_{\overline{k}|k} + \mathbf{1}^T {\psi_1^v}^T \boldsymbol{i}_{\overline{k}|k} \right)$$

The expression above is the sum of **two linear expressions and a quadratic form in the current. It is therefore convex provided that ψ is SDP**, which has been numerically proven for the adopted TTC model.

Formulation – The new (convex) MPC

We use the previous result to formulate a convex equivalency of the original MPC optimization problem. This consists in maximizing the current (linear cost function) subject to the energy throughput being less or equal to the target energy throughput e_k (convex inequality).

$$\boldsymbol{i}^o_{\overline{k}|k} = \underset{\boldsymbol{i} \in \mathbb{R}^{(k-\overline{k}+1)}}{\arg\max} \left\{ \mathbf{1}^T \boldsymbol{i}_{\overline{k}|k} \right\}$$

subject to :

$$e_k = \frac{300}{3600} \cdot \left(P^*_k - P^+_k \right) \qquad \text{(Tracking error)}$$

$$\alpha \left(x_k^T \phi^{vT} \boldsymbol{i}_{\overline{k}|k} + \boldsymbol{i}^T_{N|t} \psi_i^{vT} \boldsymbol{i}_{\overline{k}|k} + \mathbf{1}^T \psi_r^{vT} \boldsymbol{i}_{\overline{k}|k} \right) \leq e_k \quad \text{(BESS energy througput, convex if } \psi_i^v \text{ is SDP)}$$

$$\mathbf{1} \cdot i_{\min} \preccurlyeq \boldsymbol{i}_{\overline{k}|k} \preccurlyeq \mathbf{1} \cdot i_{\max} \qquad \text{(Current constraints)}$$

$$\mathbf{1} \cdot \Delta_{i,\min} \preccurlyeq H \boldsymbol{i}_{\overline{k}|k} \preccurlyeq \mathbf{1} \cdot \Delta_{i,\max} \qquad \text{(Current ramping constraints)}$$

$$\boldsymbol{v}_{\overline{k}|k} = \phi^v v_k + \psi_i^v \boldsymbol{i}_{\overline{k}|k} + \psi_1^v \mathbf{1} \qquad \text{(Voltage model)}$$

$$\mathbf{1} \cdot v_{\min} \preccurlyeq \boldsymbol{v}_{\overline{k}|k} \preccurlyeq \mathbf{1} \cdot v_{\max} \qquad \text{(Voltage constraints)}$$

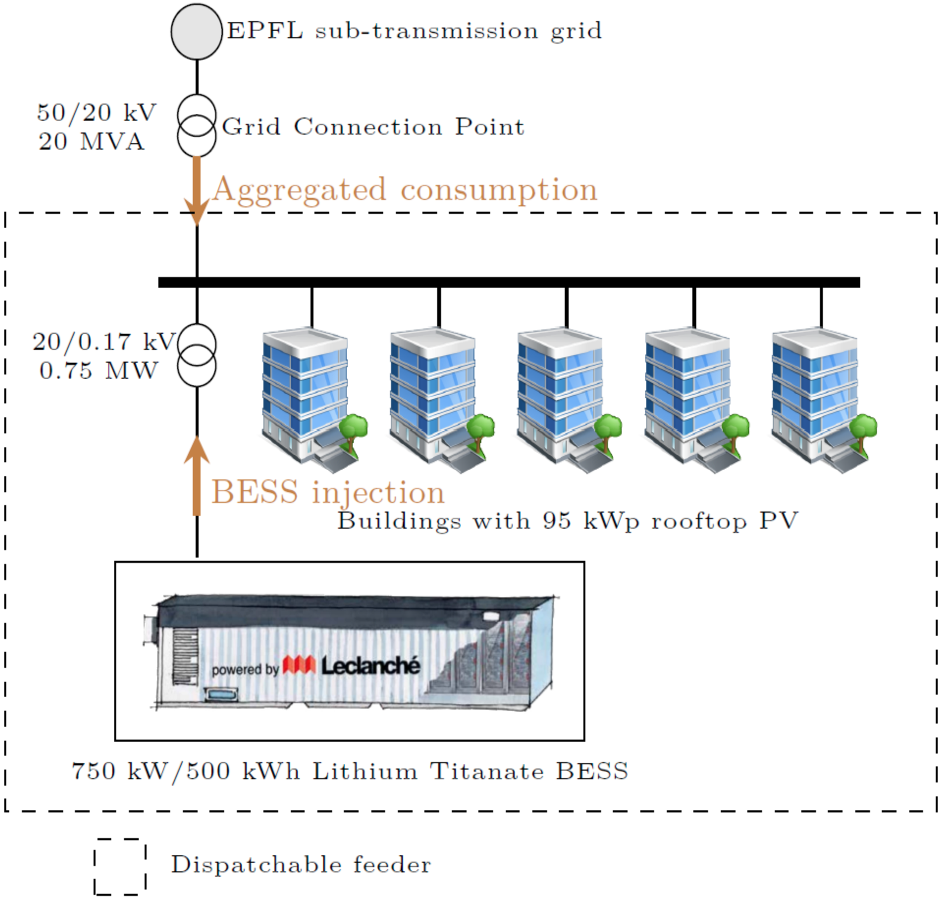
$$\mathbf{SOC}_{\overline{k}|k} = \phi^{\text{SOC}} \text{SOC}_k + \psi_i^{\text{SOC}} \boldsymbol{i}_{\overline{k}|k} \qquad \text{(SOC model)}$$

$$\mathbf{1} \cdot \text{SOC}_{\min} \preccurlyeq \mathbf{SOC}_{\overline{k}|k} \preccurlyeq \mathbf{1} \cdot \text{SOC}_{\max} \qquad \text{(SOC constraints)}$$

- **value of the prosumption set-point to match (from the dispatch plan)**
- **expected average consumption with short-term point prediction**

Once the current is known from the MPC, it is multiplied by the voltage to determine the real power set-point to finally submit to the BESS converter.

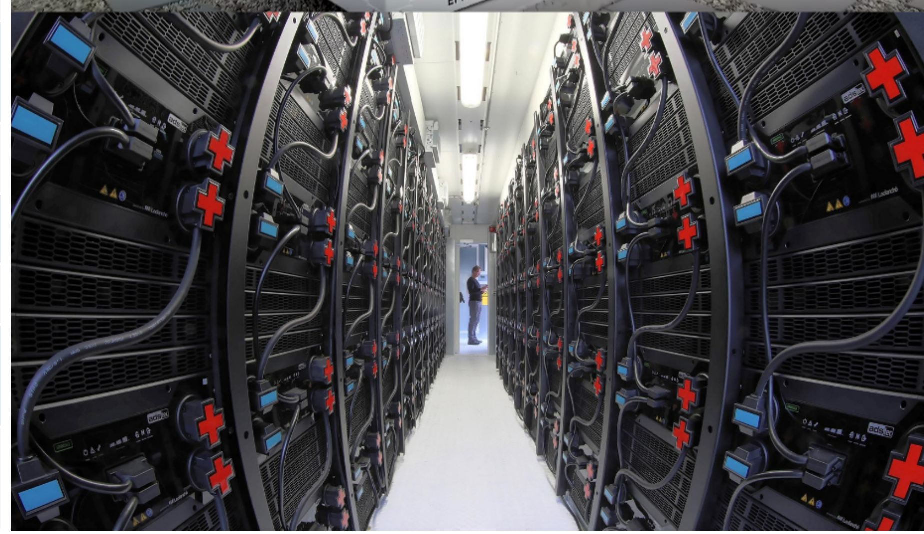
The EPFL experimental setup



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

The EPFL experimental setup – The BESS specs

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%



Results

Dispatched operation -- 14 Jan 2016
https://snapshot.raintank.io/dashboard/snapshot/PuW1Rf5d470Q0gsT7UNponM25bGDNTRA

Dispatched operation -- 13 Jan 2016
https://snapshot.raintank.io/dashboard/snapshot/cDS4IDniZjRiePXvusnmQXOmMwpGLnR6

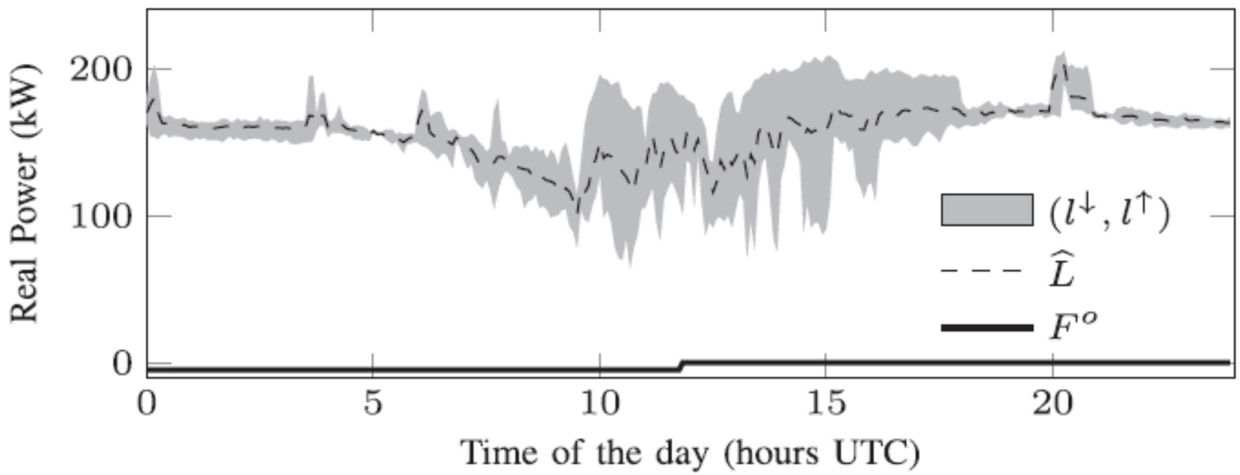
Dispatched operation + Peak Shaving -- 22/06/2016
https://snapshot.raintank.io/dashboard/snapshot/LSF3bPxtWYDjHVu6siEr1VPb92EXNkd6

Dispatched Operation + Load Levelling -- 14/03/2016
https://snapshot.raintank.io/dashboard/snapshot/4ztn800czpAzEFRzbGOmWc1A2pKeC9ab

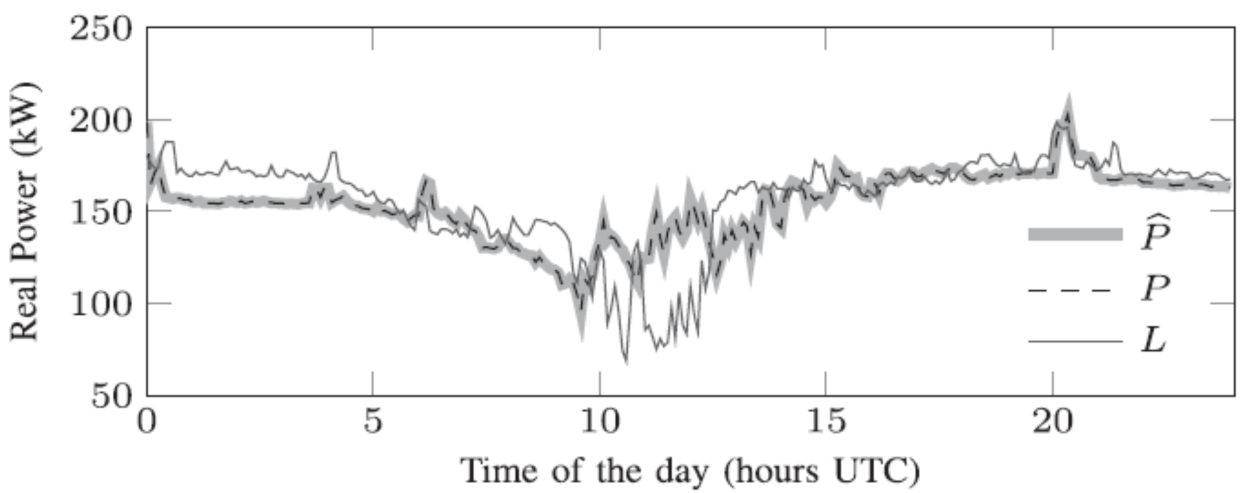
Dispatched operation (continuos operation) -- 16 to 19/03/2016
https://snapshot.raintank.io/dashboard/snapshot/TNbEgP7j1AWhaW7cEK1ZiK3tY1Or7P4U

Results – 14/01/2016, operation

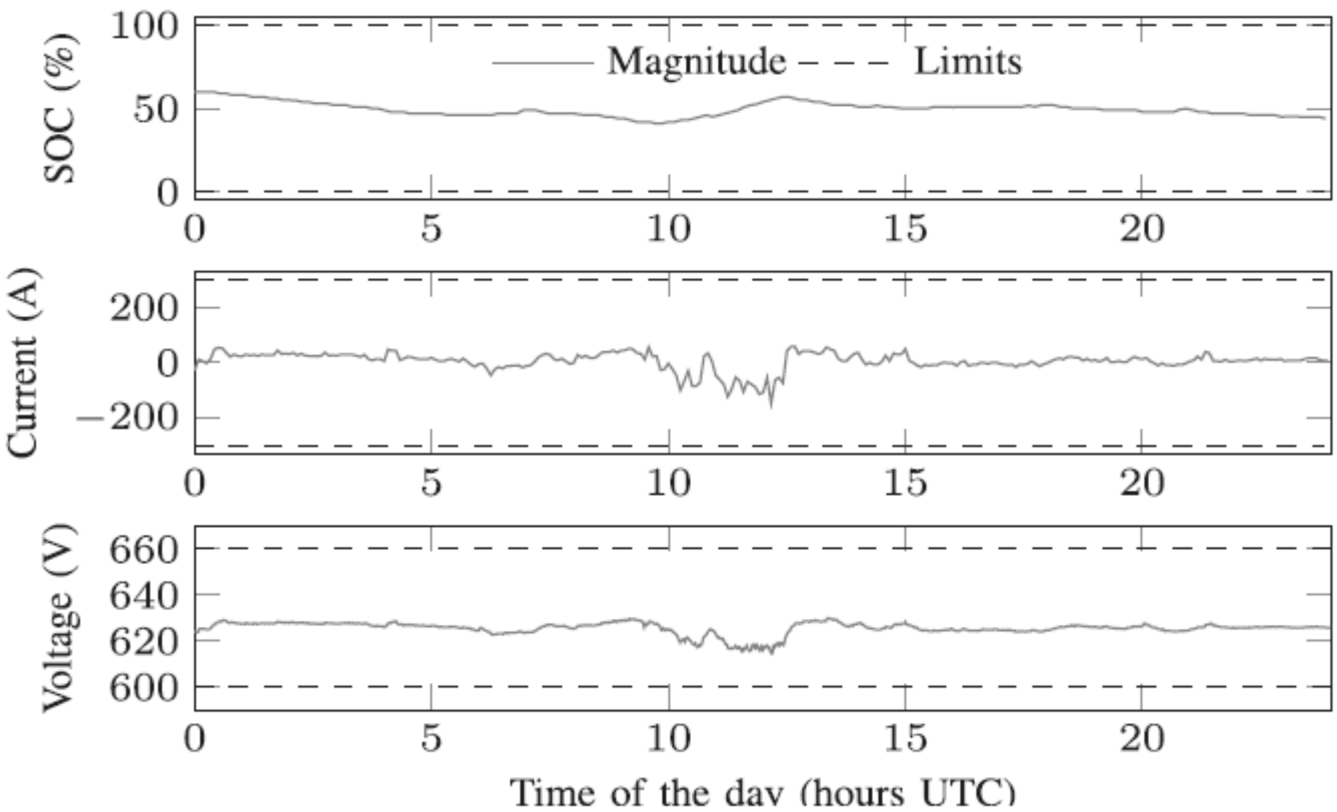
- Prosumption worst-case scenarios (shaded band)
- Prosumption point predictions (dashed)
- Offset plan (black).



- Dispatch plan (gray)
- Composite power realisation at the GCP (dashed)
- Prosumption realization without the battery correction (black)

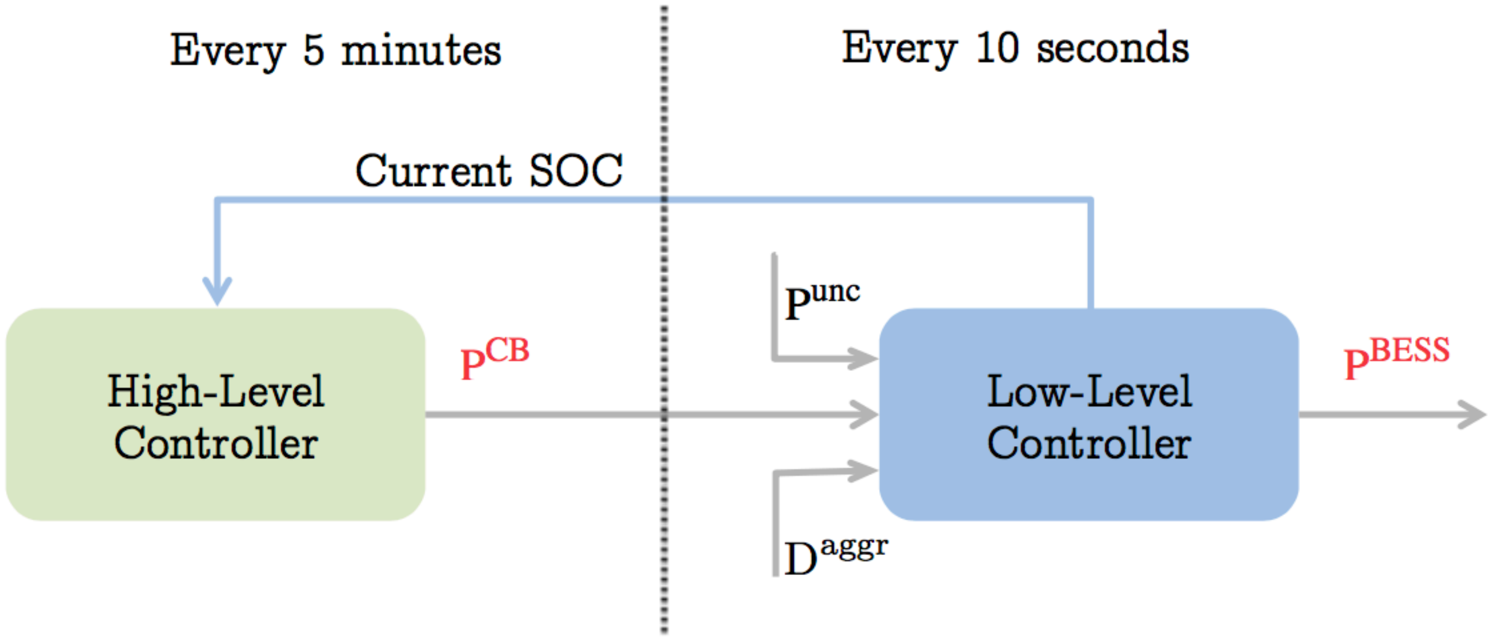


Results – 14/01/2016, BESS data



BESS state-of-charge, DC Current and DC voltage with respective limits.

Extension to multiple controllable resources



Slower control loop (coordination) for PV and building set-points.

Fast control loop for battery set-points.

Extension [...] resources – Centralized Formulation

For the case PV + Battery. Minimize PV curtailment over time while obeying to system constraints.

$$\arg\min_{\substack{G_i,\ldots,G_N \\ B_i,\ldots,B_N}} \sum_{j=i}^{N} \left(G_j - \widehat{G}_j \right)^2$$

subject to:

$$
\begin{aligned}
& B_j + G_j = e_j && j = i, \ldots, N \\
& 0 \leq G_j \leq \widehat{G}_j && j = i, \ldots, N \\
& B^{\min} \leq B_j \leq B^{\max} && j = i, \ldots, N \\
& \mathrm{SOC}_j^{\mathrm{mi}} \leq f(\mathrm{SOC}_i, \mathbf{B}_{i-1,j-1}) \leq \mathrm{SOC}_j^{\max} && j = i, \ldots, N
\end{aligned}
$$

PV output

PV short-term forecast (point prediction)

Coupling constraint

Extension [...] resources – Distributed Formulation

(Through ADMM). For the PV:

$$\boldsymbol{G}_{i,N}^{k+1} = \underset{G_i,\dots,G_N}{\arg\min} \left\{ \sum_{j=i}^{N} \left(G_j - \widehat{G}_j \right)^2 + \right.$$
$$\left. + \frac{\rho}{2} \left\| \boldsymbol{G}_{i,N} - \boldsymbol{\mathcal{G}}_{i,N}^{k} + \boldsymbol{u}_{\boldsymbol{G}_{i,N}}^{k} \right\|_2^2 \right\}$$

subject to: $0 \leq G_j \leq \widehat{G}_j \qquad j = i, \dots, N$

For the Battery:

$$\boldsymbol{B}_{i,N}^{k+1} = \underset{B_i,\dots,B_N}{\arg\min} \left\{ \frac{\rho}{2} \left\| \boldsymbol{B}_{i,N} - \boldsymbol{\mathcal{B}}_{i,N}^{k} + \boldsymbol{u}_{\boldsymbol{B}_{i,N}}^{k} \right\|_2^2 \right\}$$

subject to:

$$B^{\min} \leq B_j \leq B^{\max} \qquad j = i, \dots, N$$
$$\mathrm{SOC}_j^{\mathrm{mi}} \leq f(\mathrm{SOC}_i, \mathbf{B}_{i-1,j-1}) \leq \mathrm{SOC}_j^{\max} \qquad j = i, \dots, N$$

Distributed problems

Copied Variable update

$$[\boldsymbol{\mathcal{G}}_{i,N}^{k+1}, \boldsymbol{\mathcal{B}}_{i,N}^{k+1}] = \underset{\mathcal{G}_i,\dots,\mathcal{G}_N,\mathcal{B}_i,\dots,\mathcal{B}_N}{\arg\min} \left\{ \sum_{j=i}^{N} g_j(\mathcal{G}_j + \mathcal{B}_j) \right.$$
$$+ \frac{\rho}{2} \left\| \boldsymbol{G}_{i,N}^{k+1} - \boldsymbol{\mathcal{G}}_{i,N} + \boldsymbol{u}_{\boldsymbol{G}_{i,N}}^{k} \right\|_2^2 +$$
$$\left. \frac{\rho}{2} \left\| \boldsymbol{B}_{i,N}^{k+1} - \boldsymbol{\mathcal{B}}_{i,N} + \boldsymbol{u}_{\boldsymbol{B}_{i,N}}^{k} \right\|_2^2 \right\}$$

Dual variable update

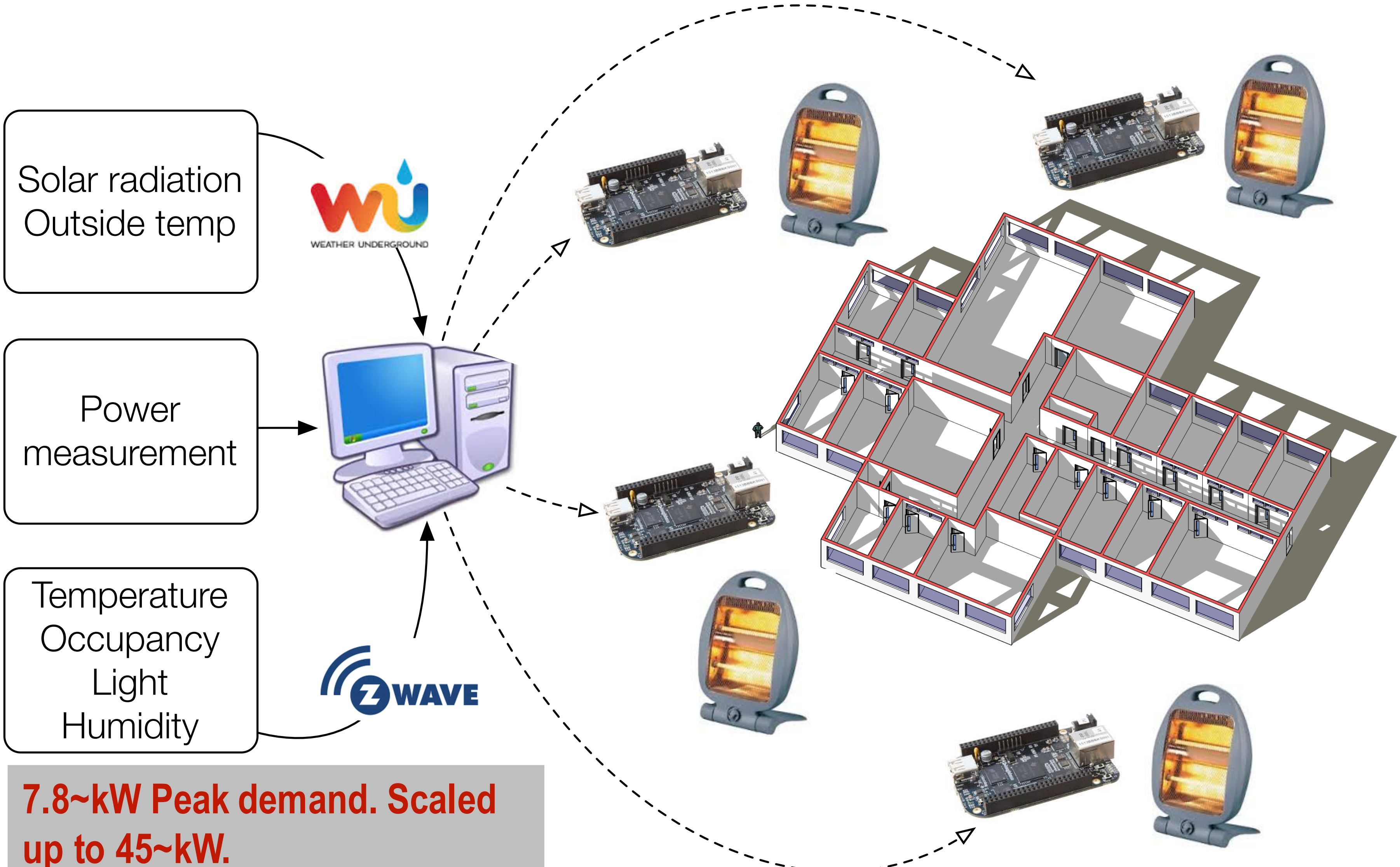
$$\boldsymbol{u}_{\boldsymbol{G}_{i,N}}^{k+1} = \boldsymbol{G}_{i,N}^{k+1} - \boldsymbol{\mathcal{G}}_{i,N}^{k+1} + \boldsymbol{u}_{\boldsymbol{G}_{i,N}}^{k}$$
$$\boldsymbol{u}_{\boldsymbol{B}_{i,N}}^{k+1} = \boldsymbol{B}_{i,N}^{k+1} - \boldsymbol{\mathcal{B}}_{i,N}^{k+1} + \boldsymbol{u}_{\boldsymbol{B}_{i,N}}^{k}$$

Centralized updates

Copied variable | Dual variable

Coupling constraint $g_j(G_j, B_j) = \begin{cases} 0, & B_j + G_j = e_j \\ \infty, & \text{otherwise} \end{cases}$

Laboratoire d'Automatique Demand Response



7.8~kW Peak demand. Scaled up to 45~kW.

Equivalent Storage Capacity of common TCLs

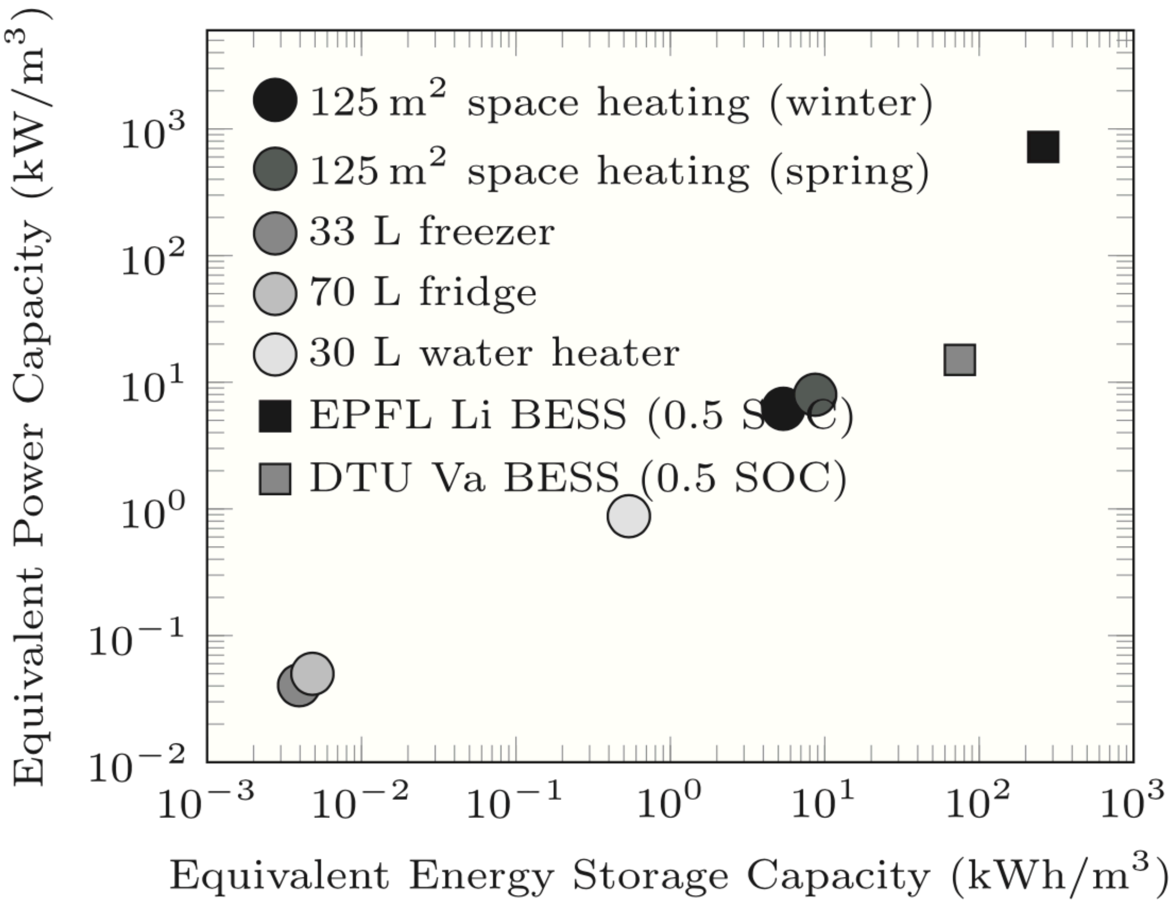
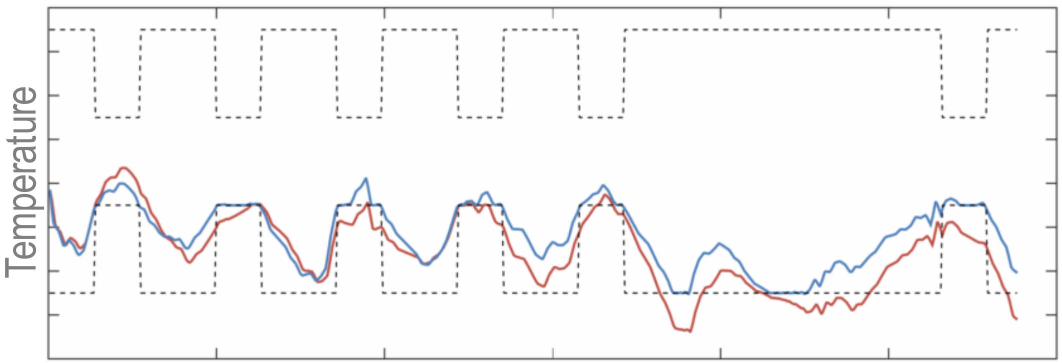


Fig.: Storage capacity of reference TCLs vs reference battery systems.

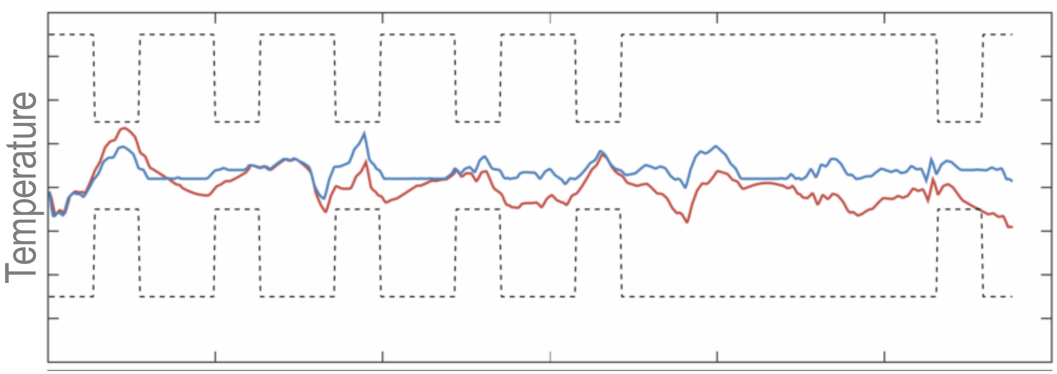
(Fabrizio Sossan. Equivalent electricity storage capacity of domestic thermostatically controlled loads. Energy, 122, 2017)

Dispatch Planning – Two Competing Objectives

❶ Minimize **energy**



❷ Maximize **flexibility**



	Cost	Comfort	Flexibility
❶ Minimize energy	Low	Low	Low
❷ Maximize flexibility	High	High	High

Goal: Choose dispatch plan to maximize controllability during highly uncertain periods

Optimal Dispatch Problem

Day-ahead plan for the thermal (x, e) trajectory of the building and electrical dispatch d

Energy cost

Comfort metric

Dispatch error

Building dispatch plan

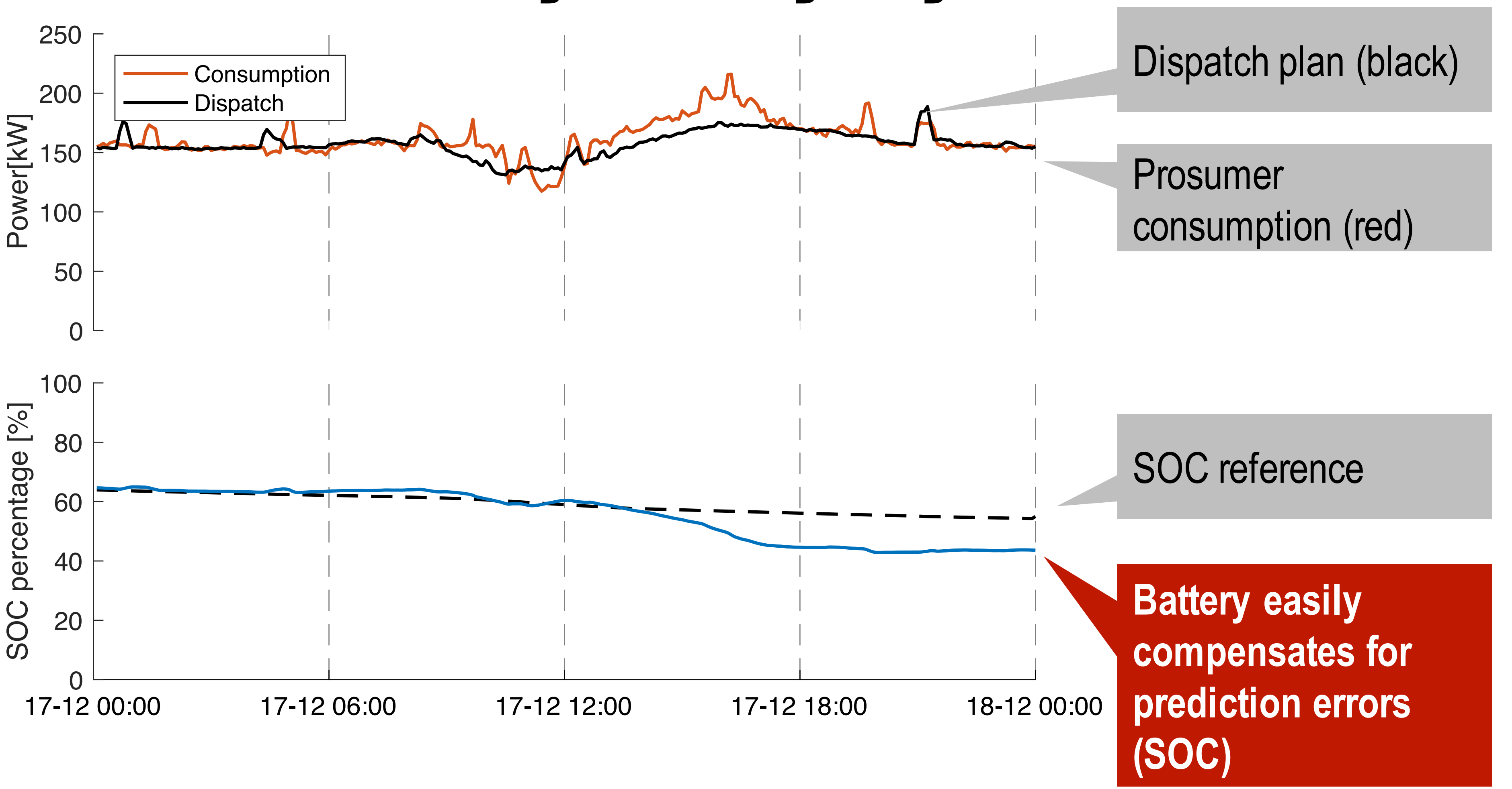
Prosumer forecast error

$$\min_{x,u} \sum \mathbb{E}\left(\text{cost}_i \cdot e_i + \rho(x_i - \bar{x}) + \|e_i - (d_i + p_i)\|^2\right)$$

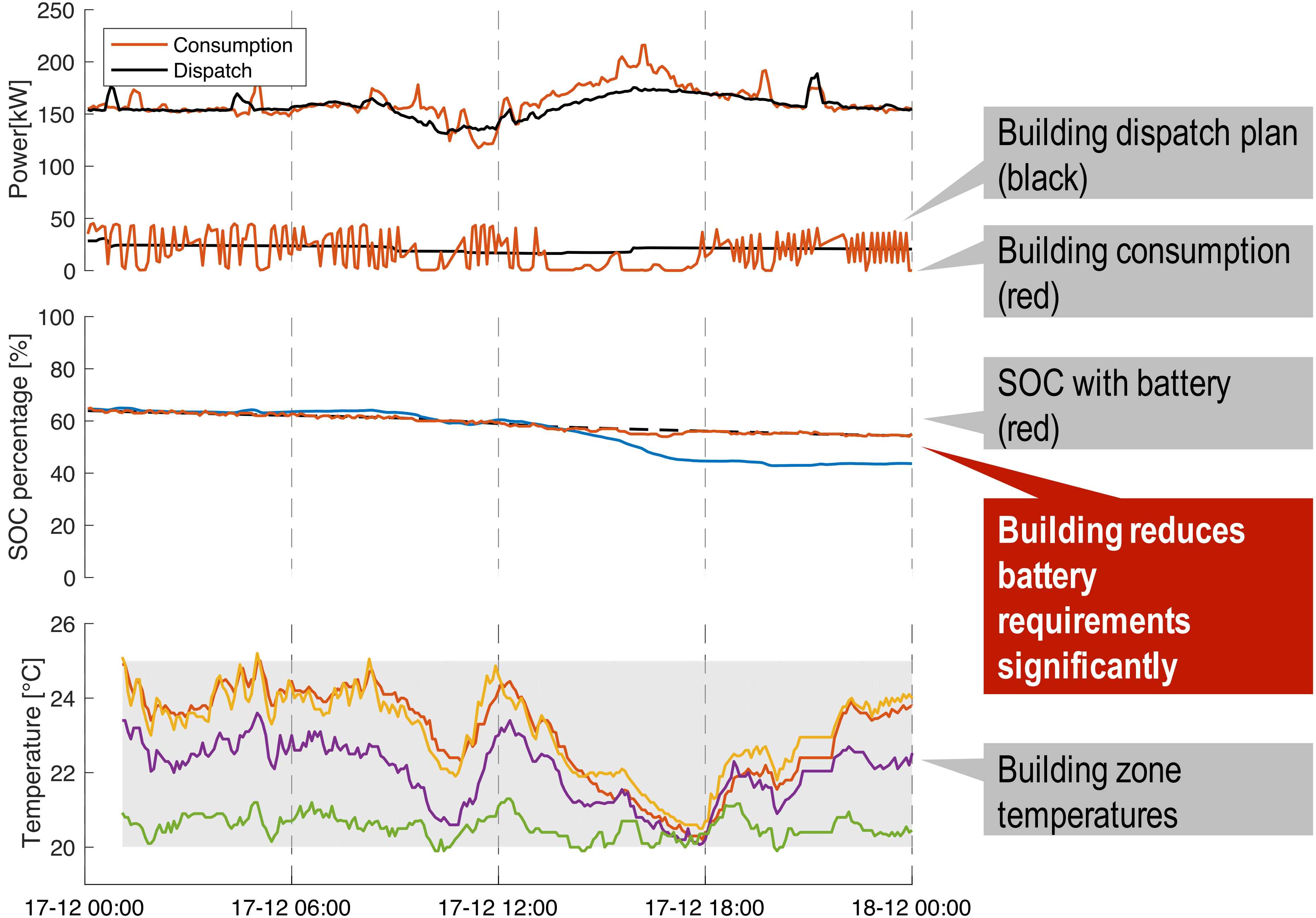
$$\text{s.t. } (x, e) \in C(w) \quad \forall w \in W$$

Thermal trajectory must be input-admissible (feasible) and comfortable $C(w)$ for all likely weather scenarios W

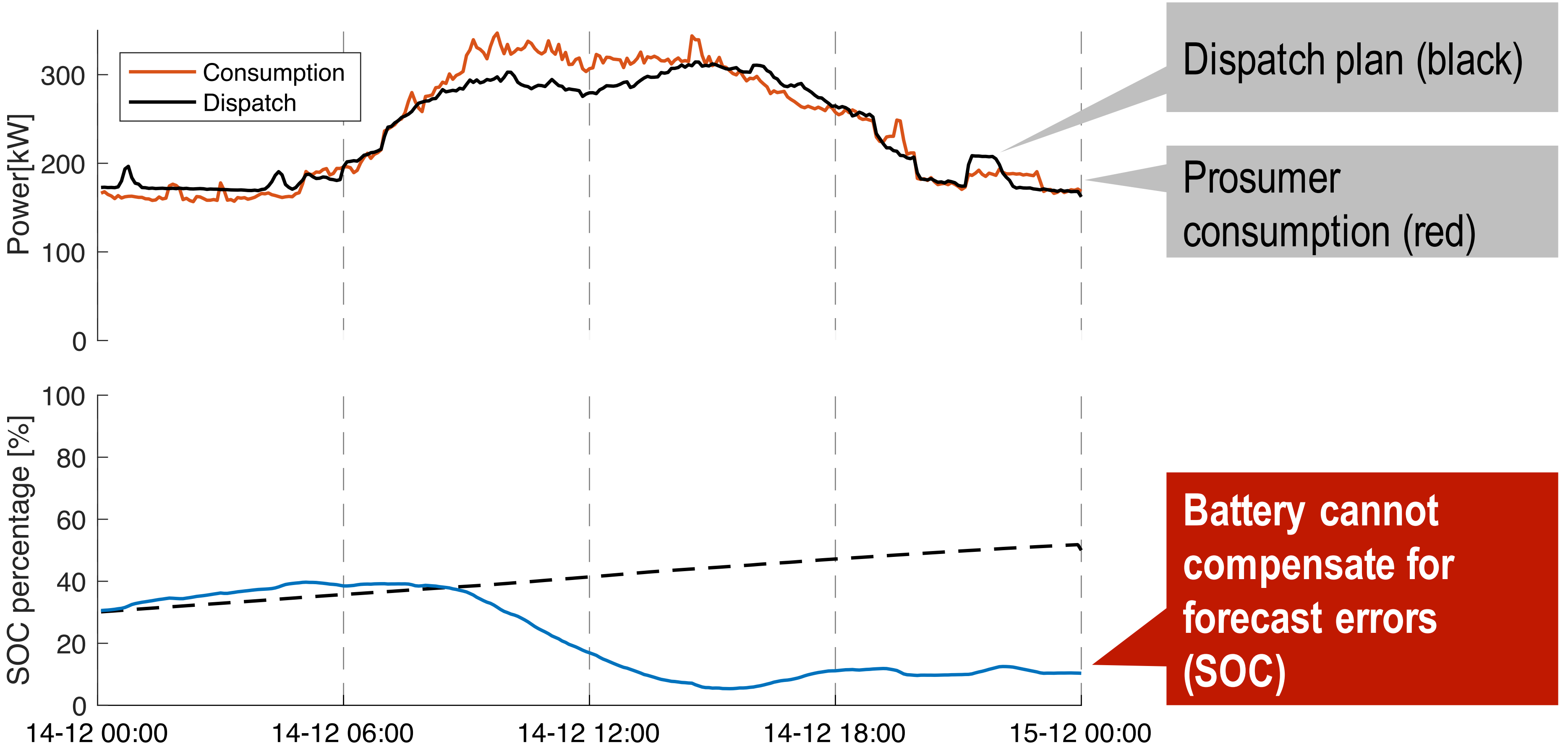
Good Prediction Day – Battery Only



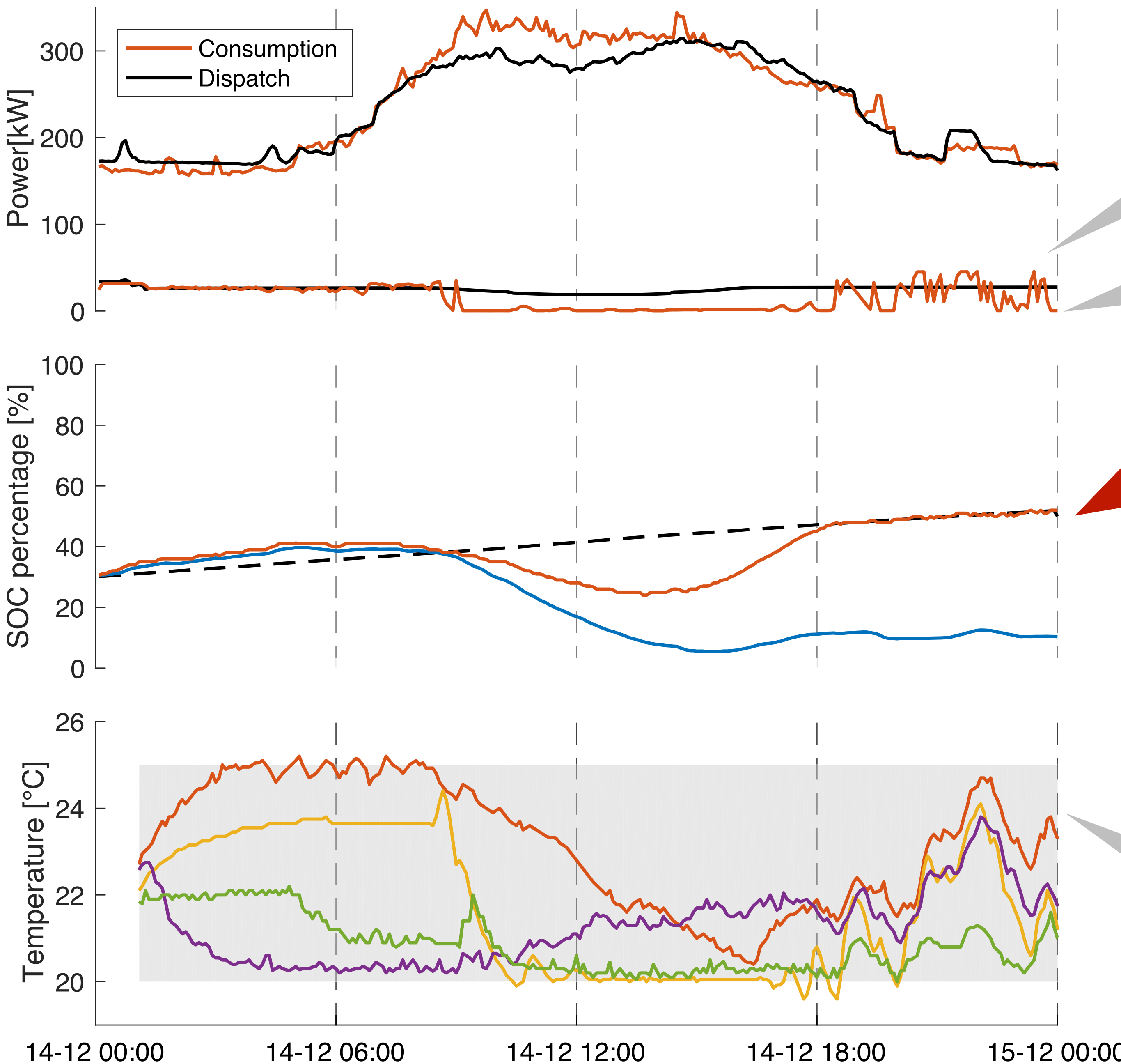
Good Prediction Day – Battery & LADR



Poor Prediction Day – Battery Only



Poor Prediction Day – Battery & LADR



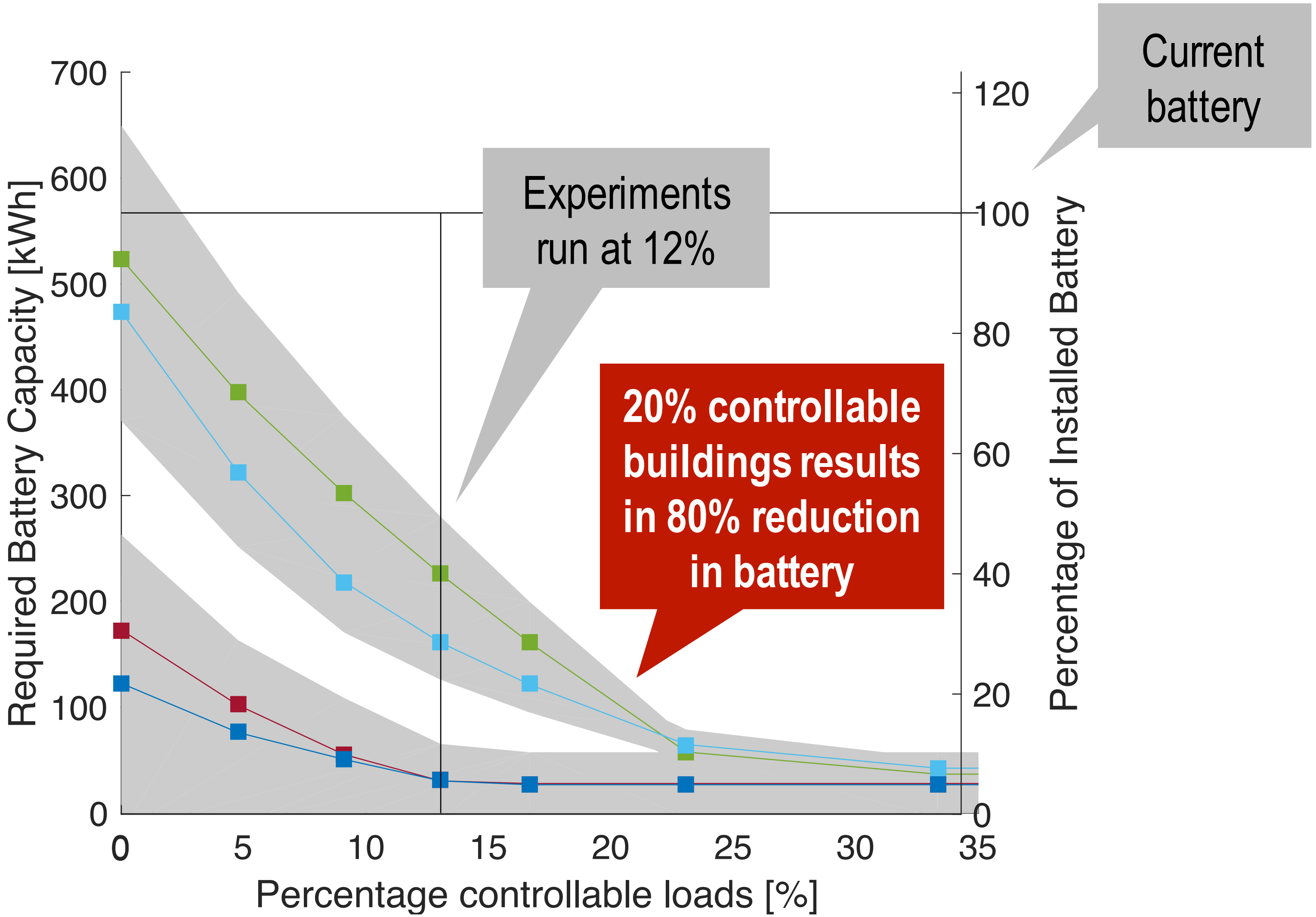
Building dispatch plan (black)

Building consumption (red)

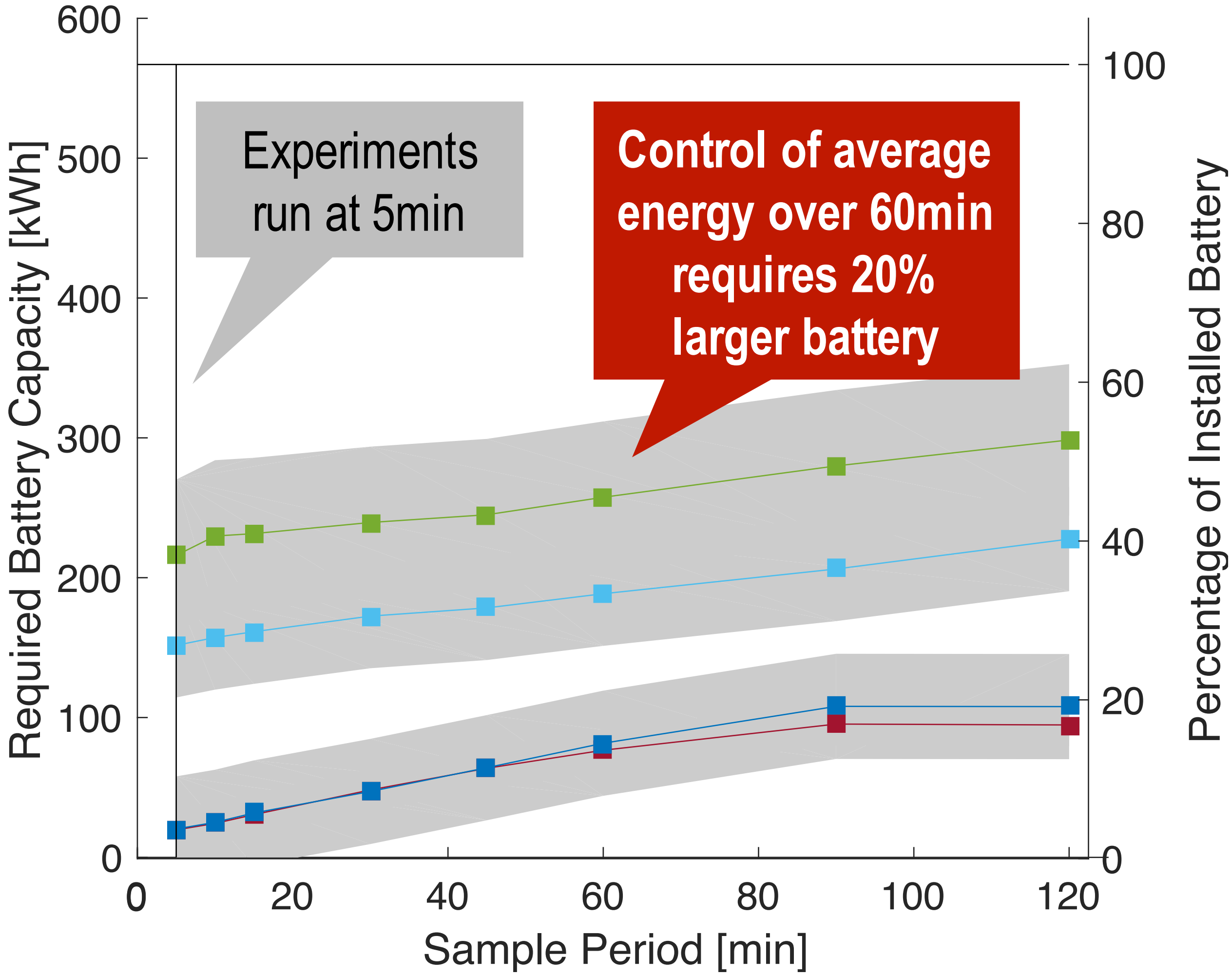
Building reduces battery requirements significantly (SOC)

Building zone temperatures

Impact of Building Size – ***Preliminary*** Conclusion



Impact of Sample Rate – *Preliminary* Conclusion



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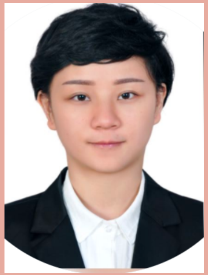
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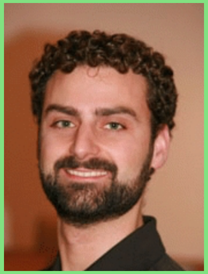
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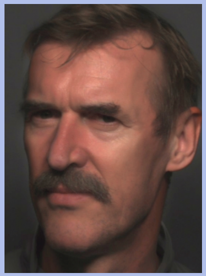

Prof. Jean-Yves **Le Boudec**

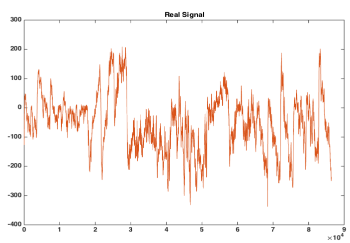
Key Conclusions

- A **bottom-up approach** to tackle the challenge of increasing reserve requirements due to integration of larger shares of renewables.
- Suitable to operate in current **vertically operated power systems**.
- **Fully decentralized control mechanism.** No coordination requirements (complexity is masked behind the commitment of the operator to follow the dispatch plan). No pervasive monitoring/control infrastructure.
- Inherently allows to achieve **local grid operational objectives**, like peak shaving or load levelling, including grid constraints (see Stai).

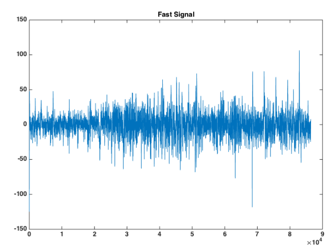
Key Conclusions – cont'd

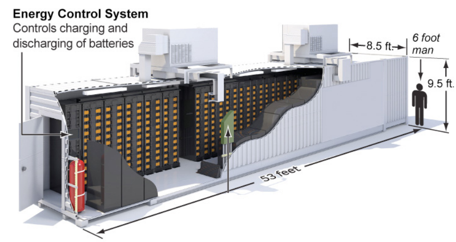
- Two-time-scale distributed optimization efficiently achieves to decouple flexibility and meet technical constraints of heterogeneous DERs.

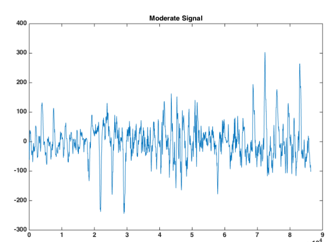
Tracking signal



Spectral Split







	Power	Energy	Time
Fast signal	High ✓	Low ✗	Fast ✓
Moderate signal	Slow ✗	High ✓	Slow ✗

SCCER - FURIES

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For info and registration:

http://sccer-furies.epfl.ch/

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Thank you for the attention. For further info:

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