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Energy management of a grid-connected PV plant coupled with a battery energy storage device using a stochastic approach

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Extension of the paper submitted to PMAPS 2020

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Capacity firming context

System
-> **PV/wind generation** + **energy storage system**

Where ?
-> **Remote areas**: French islands (Réunion, Corse, Guadeloupe, etc)

Goal
-> The **intermittent** power from a PV/wind plant has to be **maintained** at a **committed level**.

How ?
-> The **energy storage system** smoothes the output and controls the ramp rate (MW/min).

Who ?
-> The **French Energy Regulatory Commission** defines the specifications of the tenders https://www.cre.fr/.

Summary

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Literature review: day ahead bidding

The optimal bidding strategies with only a **production device:**[1,2].

[1] P. Pinson, C. Chevallier, and G. N. Kariniotakis, "Trading wind generation from short-term probabilistic forecasts of wind power," IEEE Transactions on Power Systems, vol. 22, no. 3, pp. 1148–1156, 2007.
[2] A. Giannitrapani, S. Paoletti, A. Vicino, and Zarrilli, "Bidding wind energy exploiting wind speed forecasts," IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 2647–2656, 2015.

Incorporating an **energy storage** and dealing with the **uncertainties**: SDDP/SDP [3]/[4], chanced-constrained [5], **2-stage stochastic** [6], robust optimization [7,8].

[3] M. V. Pereira, L. M. Pinto, Multi-stage stochastic optimization applied to energy planning, Mathematical programming 52 (1- 3) (1991) 359–375.
[4] P. Haessig, B. Multon, H. B. Ahmed, S. Lascaud, P. Bondon, Energy storage sizing for wind power: impact of the autocorre- lation of day-ahead forecast errors, Wind Energy 18 (1) (2015) 43–57.
[5] F. Conte, S. Massucco, F. Silvestro, Day-ahead planning and real-time control of integrated pv-storage systems by stochastic optimization, IFAC-PapersOnLine 50 (1) (2017) 7717–7723.
[6] A. Parisio, E. Rikos, L. Glielmo, Stochastic model predictive control for economic/environmental operation management of microgrids: An experimental case study, Journal of Process Control 43 (2016) 24–37.
[7] D. Bertsimas, E. Litvinov, X. A. Sun, J. Zhao, T. Zheng, Adaptive robust optimization for the security constrained unit commitment problem, IEEE transactions on power systems 28 (1) (2012) 52–63.
[8] R.Jiang, J.Wang, Y.Guan, Robust unit commitment with wind power and pumped storage hydro, IEEE Transactions on Power Systems 27 (2) (2011) 800–810.

Mixed integer quadratic programming, simulation-based genetic algorithm, and expert-based heuristic are compared in [9].

[9] A. N'Goran, B. Daugrois, M. Lotteau, S. Demassey, Optimal engagement and operation of a grid-connected PV/battery system, in: 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), IEEE, 1–5, 2019.

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Contributions: PMAPS 2020 paper + extension

2 layers approach:

- **2-stage stochastic** planner scenario based approach -> **day-ahead** bidding;
- **deterministic** controller -> **real-time** set points.

Formulation:

- **Mix Integer Quadratic Programming** (MIQP);
- linear constraints to approximate a non-convex penalty function, **compatible** with a **scenario approach**.

PV scenarios:

- **Gaussian copula** methodology based on the **parametric** PVUSA model using a weather **regional climate model**.

2-stage **stochastic** planner vs **deterministic** counterpart:

- oracle = using perfect knowledge of the future;
- PV point forecasts.

Summary

1. Literature review
2. Capacity firming process
3. Problem formulation
4. Case study
5. Conclusions & perspectives

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Day ahead engagement process

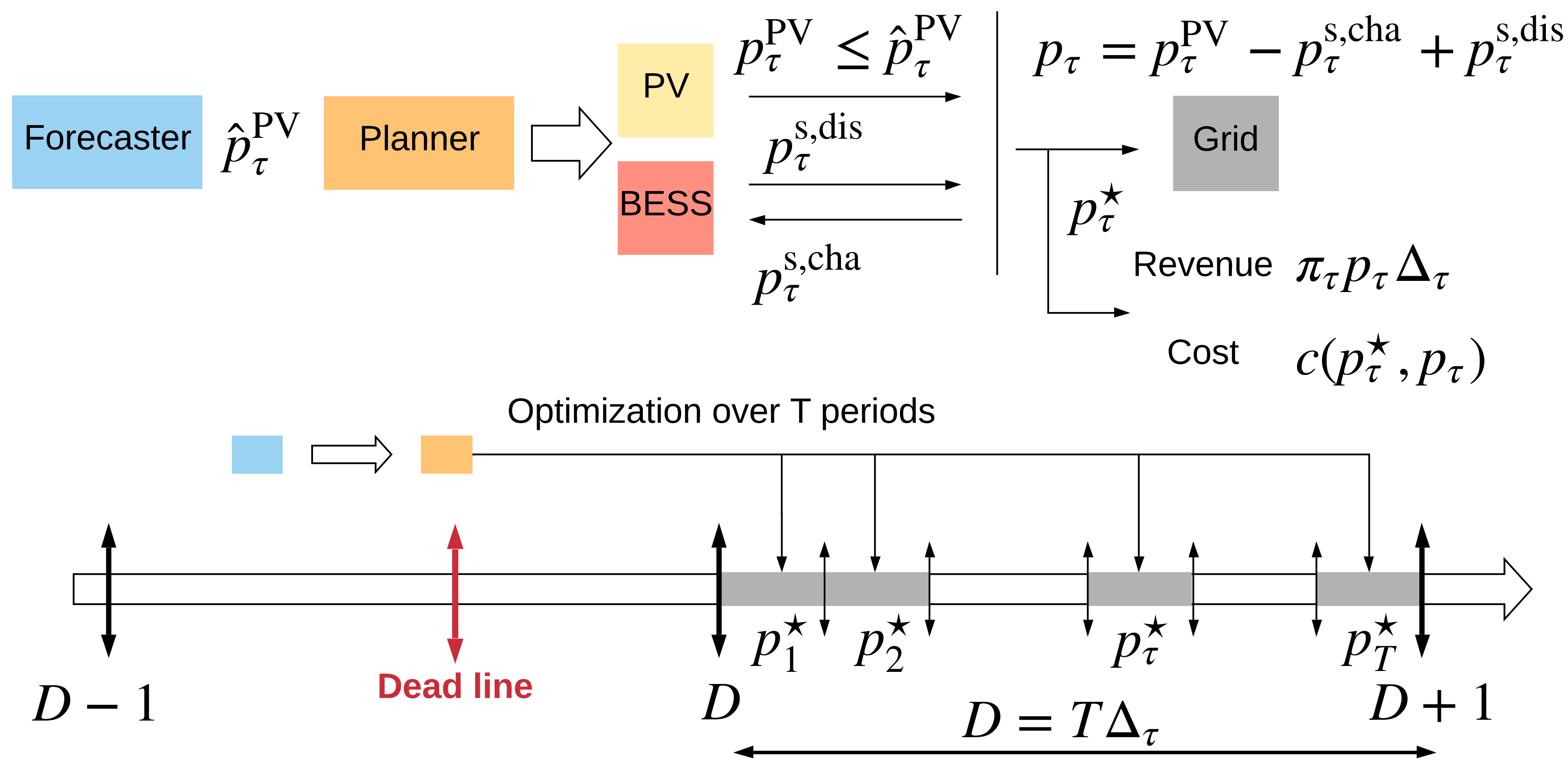

Figure 1: Day ahead engagement process.

The engagement plan is accepted if it satisfies **the constraints**

$$|p_\tau^\star - p_{\tau-1}^\star| \leq \Delta_{p,\tau}^\star \quad (1a)$$

$$-p_\tau^\star \leq -P_\tau^{\star,-} \quad (1b)$$

$$p_\tau^\star \leq P_\tau^{\star,+}, \quad (1c)$$

Real-time process

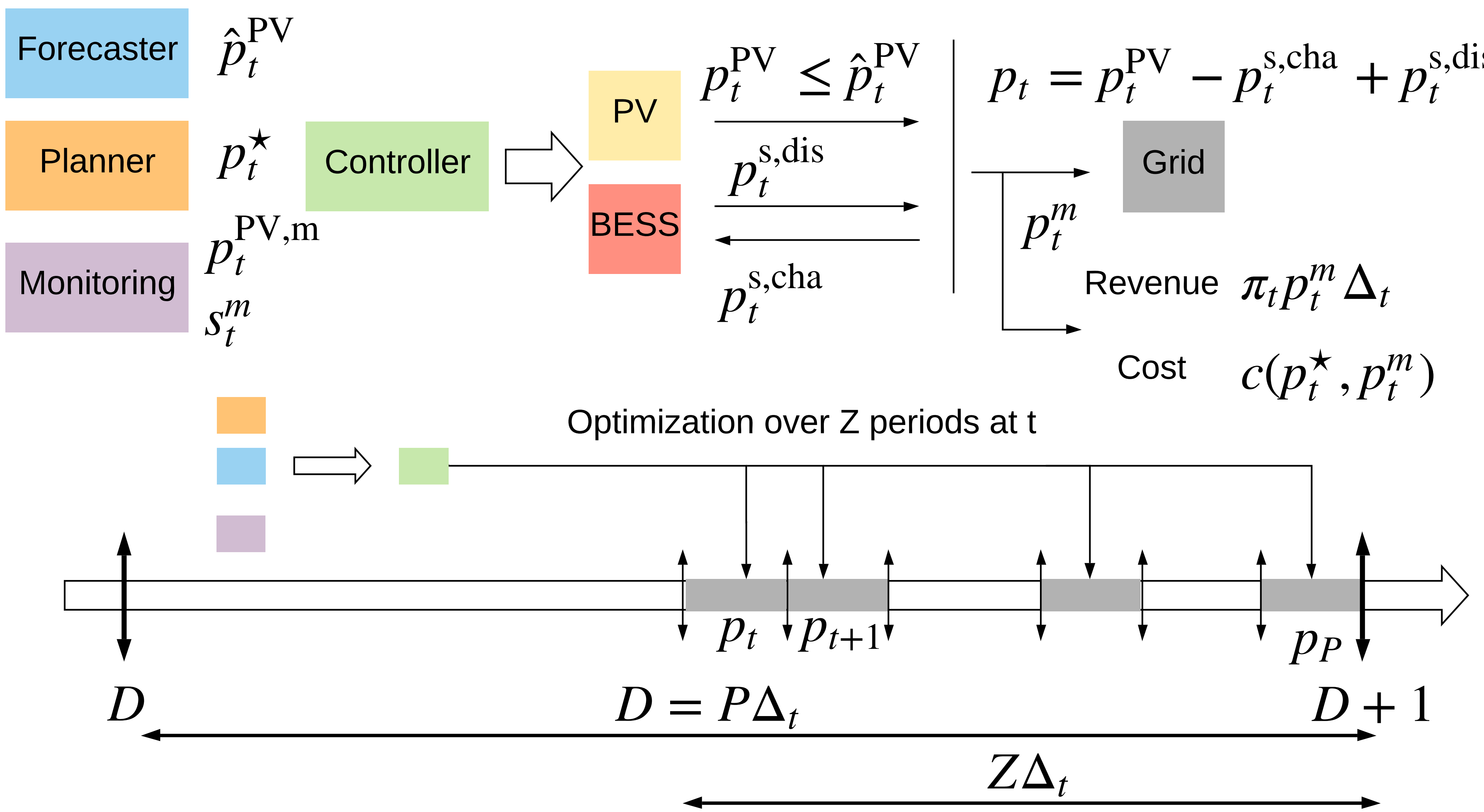

Figure 2: Real-time control process.

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Penalty and revenue

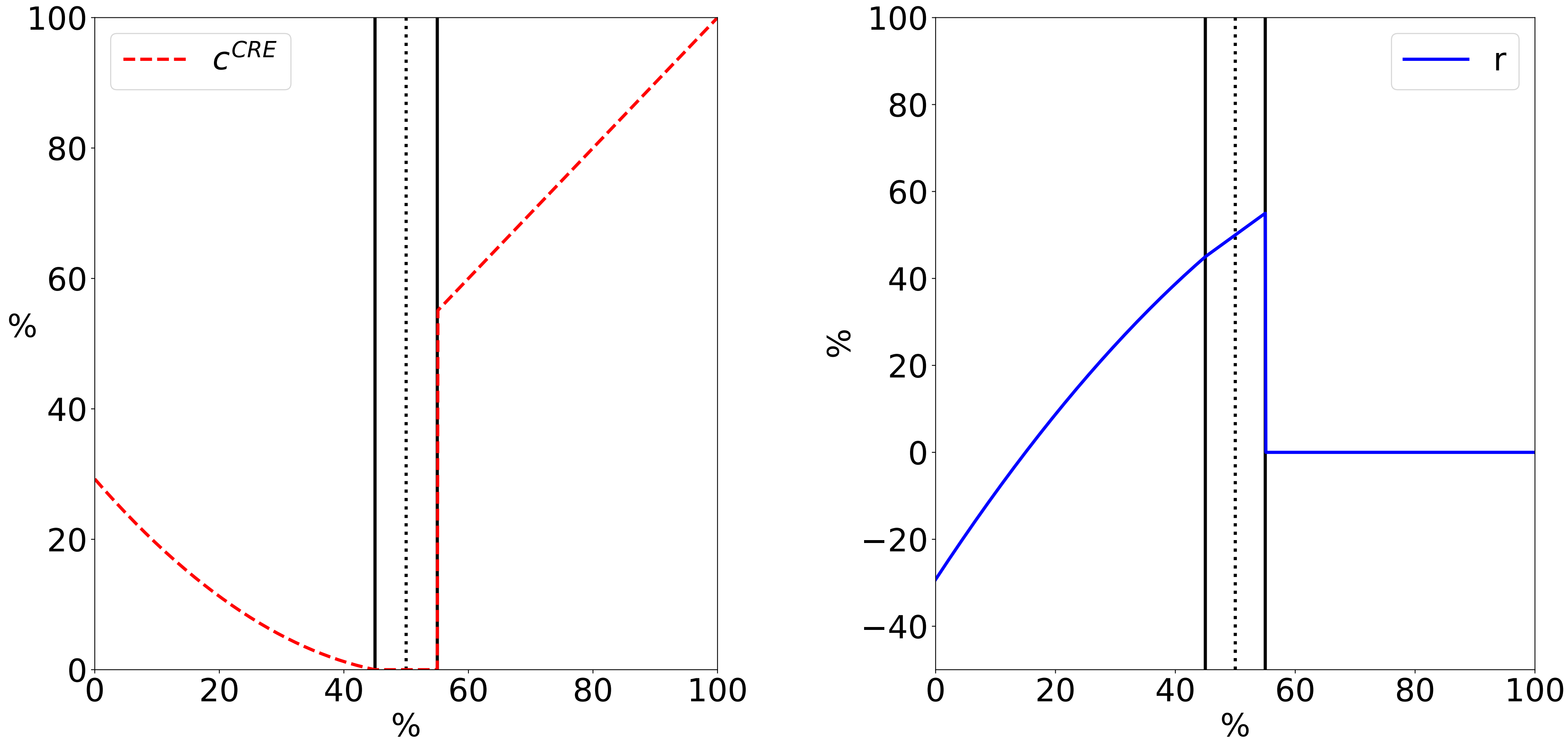

Figure 3: Penalties (left) and net revenues (right).
Engagement = 50 % of PV installed capacity, deadband tolerance = 5%.

$$r_t = \Delta_t \pi_t p_t^{\mathrm{m}} - c(p_t^{\star}, p_t^{\mathrm{m}}), \ \forall t \in \mathcal{P}. \qquad (2)$$

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Formulation: day ahead nomination

The objective **2-stage stochastic** (S) programming using a **scenario approach** is

$$J_S = \sum_{\omega \in \Omega} \alpha_\omega \sum_{\tau \in \mathcal{T}} \Big[\underbrace{-\Delta_\tau \pi_\tau p_{\tau,\omega}}_{\text{Revenue}} + \underbrace{c(p_\tau^\star, p_{\tau,\omega})}_{\text{Penalty}} \Big] \quad (3)$$

The objective **deterministic** (D=S with one scenario) counterpart is

$$J_D = \sum_{\tau \in \mathcal{T}} -\Delta_\tau \pi_\tau p_\tau + c(p_\tau^\star, p_\tau) \quad (4)$$

(3)-(4) are **Mix Integer Quadratic Problems** (MIQP). The S formulation uses PV scenarios, and the D formulation uses PV point forecasts.

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Formulations: real-time control

The **oracle** (= D planner) assumes **perfect knowledge** of PV and uses day ahead **engagements** as **inputs**

$$J^{oracle} = \sum_{t \in \mathscr{P}} - \Delta_t \pi_t p_t + c(p_t^{\star}, p_t) \ (5)$$

The **real-time controller** (RT) uses the **last PV measured** value, the **PV point forecasts**, and day ahead **engagements**, for t in [1, P]

$$J^{RT} = \sum_{t \in \mathscr{P} \setminus \{1, \ldots, t-1\}} - \Delta_t \pi_t p_t + c(p_t^{\star}, p_t) \ (6)$$

WARNING: RT should use **intraday PV point forecasts** updates to compute re-engagements (not available in the case study).

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The Uliège case study: dataset

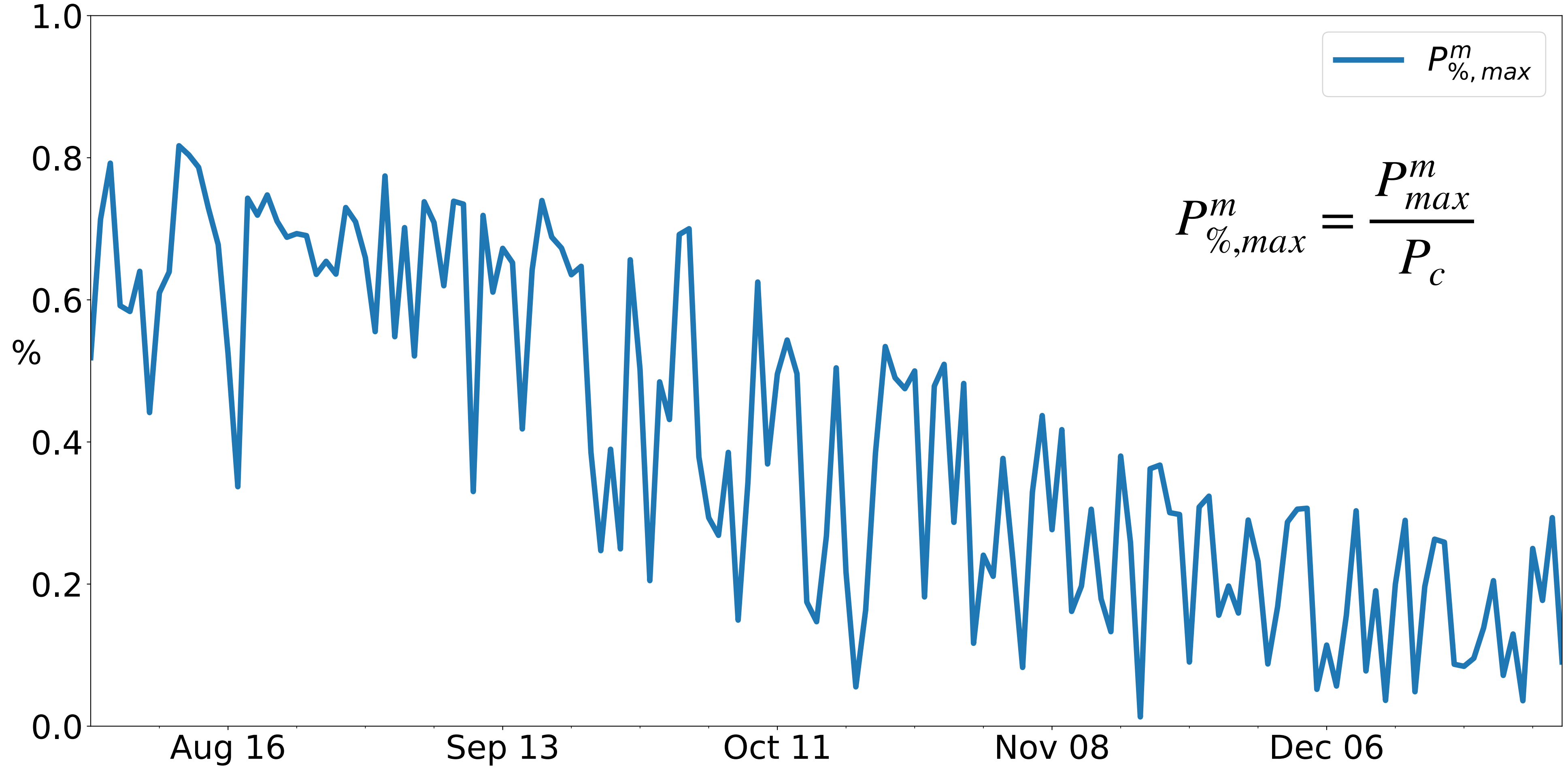

Figure 4: PV max per day of the Liège dataset.

- 08-12/2019: **4 months**
- **1 min** resolution monitored on site
- Pc = **466,4** kWp

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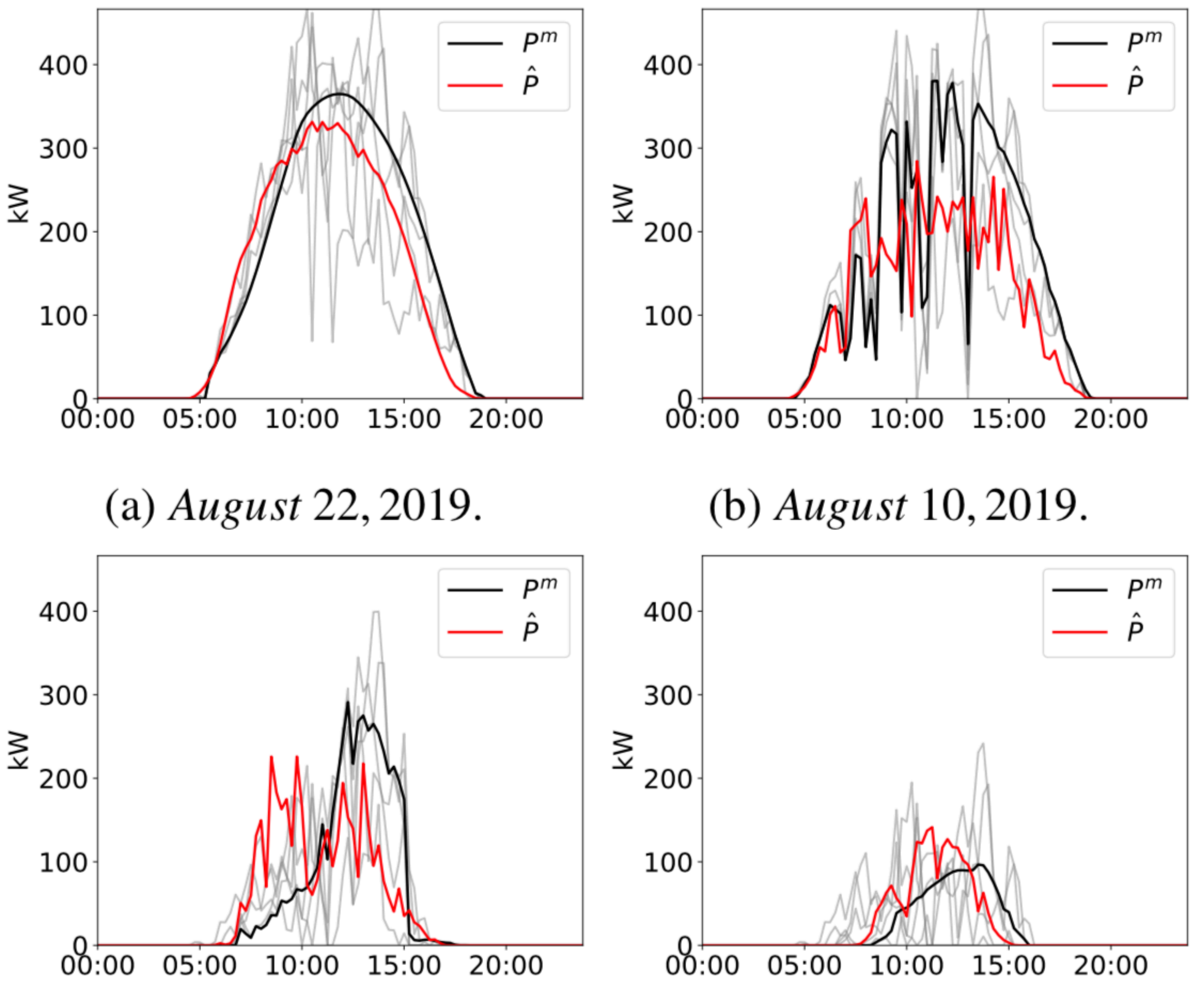
PV scenarios



(a) *August* 22, 2019. (b) *August* 10, 2019.

(c) *September* 30, 2019. (d) *December* 10, 2019.

Figure 5: Set of 5 PV scenarios.

Red = **PVUSA** point forecast
Black = PV **measurement**
Grey = 5 PV **scenarios**

PVUSA:
NMAE = 4.25 %
NRMSE = 9.20 %

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Simulation parameters

Simulation parameters:

- Pc = **466,4** kWp
- Planning and controlling periods = **15 min**
- Peak hours: **7 - 9 pm**
- Selling price = **100** €/MWh (**300** during peak hours)
- Deadband engagement tolerance = **5 % Pc**
- Engagement ramping constraints = **7.5 % Pc/15min**

BESS parameters:

- capacity = **Pc * 1 hour** = **466.4 kWh**
- charging and discharging efficiencies = **0.95**
- charging and discharging power = **Pc = 466.4** kW
- initial state of charge = **0** kWh each day
- state of charge of the last period = **0** kWh each day

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Computation times

Table 1: Computation times.

$\lvert\Omega\rvert$	1	5	20	50
# variables (k) $\approx$	1	4	15	40
# constraints (k) $\approx$	1.5	6	22	55
$\bar{t}_{\text{CPU}}$ *(s)*	0.1	0.5	3	10
$t_{\text{CPU}}^{\max}$ *(s)*	0.3	1	7	30

Solver & software:

- **Cplex** (MIQP)
- **Pyomo python** library
- Ubuntu 18.04 LTS
- Intel core i7-8700 3.20 GHz based computer with 12 threads and 32 GB of RAM

Day ahead engagement **computation time is not an issue**.

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Results

Table 2: Indicators.

Name	Description	Unit
J	Daily objective.	k€
c	Penalty cost.	k€

Table 3: Results.

oracle	$D^\star$	D	S^5	S^{20}	S^{50}
$[J]$	-26.75	-26.38	-26.36	-26.41	-26.40
$[c]$	0.02	0.23	0.25	0.20	0.23
RT	$D^\star$	D	S^5	S^{20}	S^{50}
$[J]$	-25.20	-24.88	-24.86	-24.88	-24.85
$[c]$	-0.19	0.5	0.57	0.51	0.54

S^20 and D **achieved similar** results both with the oracle and RT controllers.

Conclusions & extensions

The **2-stage stochastic** approach achieved **similar** results than its deterministic counterpart.

-> At least **one full year of data** are required to produce « good » PV scenarios (seasonality).

-> **Intraday weather forecast updates** are required to compute re-engagements and run « properly » the **RT** controller.

-> Extension to a **robust formulation** is currently underwork using quantile PV generation forecasts.

Annex

1. Weather forecasts
2. PV point forecasts
3. PV scenarios

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Weather forecasts: MAR regional climate model

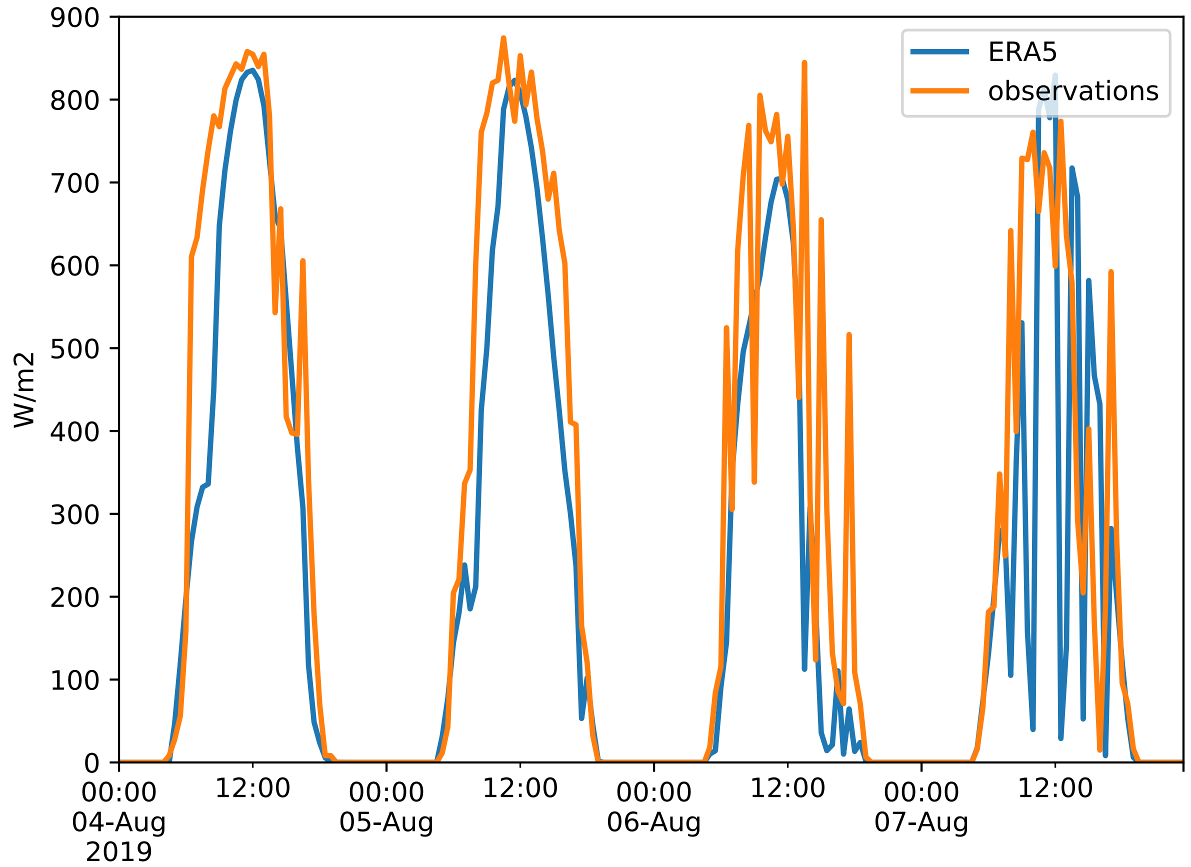

Figure 6a: Irradiation.

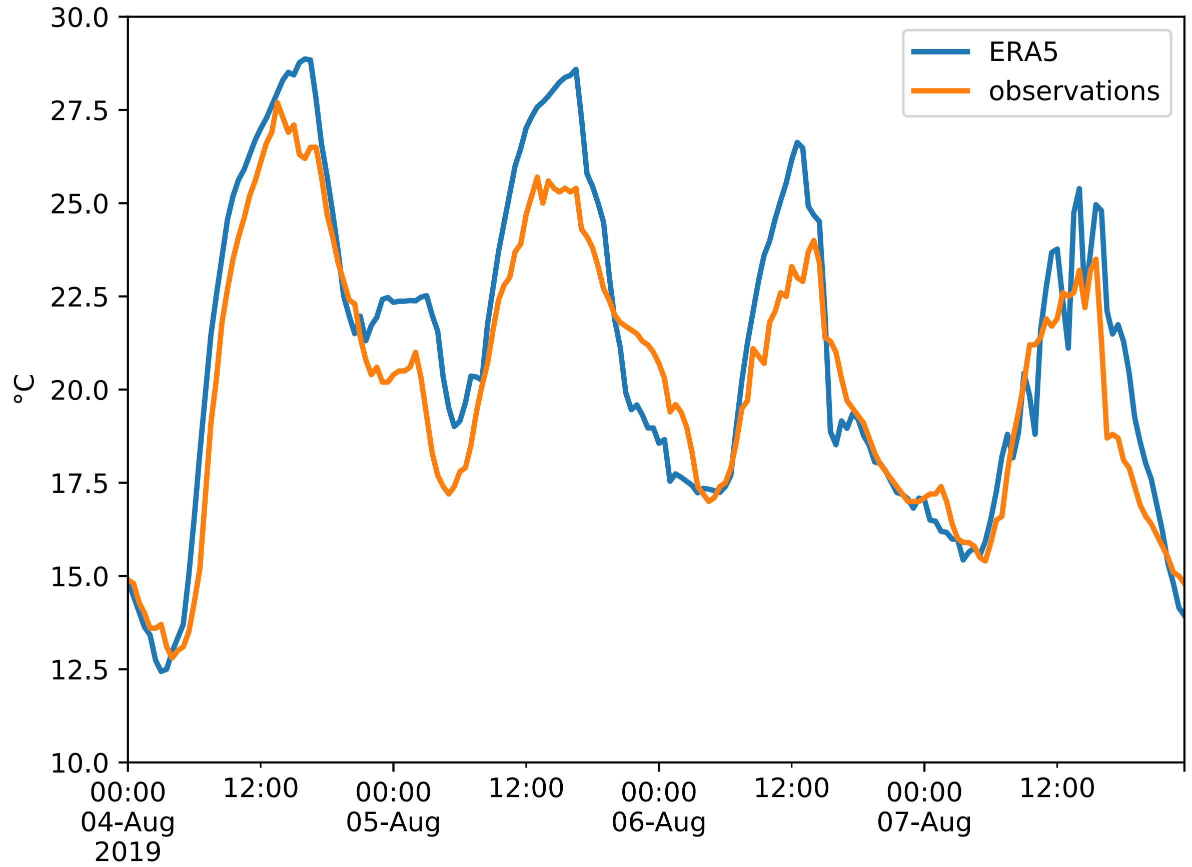

Figure 6b: Air temperature.

MAE = 70 (W/m2)
RMSE = 128 (W/m2)

MAE = 1.29 (°C)
RMSE = 1.56 (°C)

PV point forecasts

PV point forecasts are computed using the **PVUSA model** [10] which expresses the instantaneous generated power as a **function of irradiance and air temperature** according to the equation

$$\hat{P} = a\hat{I} + b\hat{I}^2 + c\hat{I}\hat{T} \quad (7)$$

[10] R.Dows, E.Gough, PVUSA procurement, acceptance, and rating practices for photovoltaic power plants, Tech. Rep., Pacific Gas and Electric Co., San Ramon, CA (United States). Dept. of ..., 1995.

The PVUSA parameters (a, b, and c) are estimated following the algorithm of [11]. **Weather forecasts** are provided by the Laboratory of Climatology of the university of Liège, based on the **MAR regional climate model** [12], http://climato.be/cms/index.php?climato=fr_previsions-meteo.

[11] G.Bianchini, S. Paoletti, A. Vicino, F. Corti, F. Nebiacolombo, Model estimation of photovoltaic power generation using partial information, in: IEEE PES ISGT Europe 2013, IEEE, 1–5, 2013.
[12] X. Fettweis, J. Box, C. Agosta, C. Amory, C. Kittel, C. Lang, D. van As, H. Machguth, H. Galle´e, Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model, Cryosphere (The) 11 (2017) 1015–1033.

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PV scenarios

The Gaussian copula methodology has already been used to generate wind and PV scenarios in, e.g., [13,16].

This approach is used to **sample PV error scenarios** (Z) based on a point forecast model.

[13] P. Pinson, H. Madsen, H. A. Nielsen, G. Papaefthymiou, B. Klöckl, From probabilistic forecasts to statistical scenarios of short-term wind power production, Wind Energy: An Inter- national Journal for Progress and Applications in Wind Power Conversion Technology 12 (1) (2009) 51–62.
[14] P.Pinson,R.Girard, Evaluating the quality of scenarios of short-term wind power generation, Applied Energy 96 (2012) 12–20.
[15] G. Papaefthymiou, D. Kurowicka, Using copulas for modeling stochastic dependence in power system uncertainty analysis, IEEE Transactions on Power Systems 24 (1) (2008) 40–49.
[16] F. Golestaneh, H. B. Gooi, P. Pinson, Generation and evaluation of space–time trajectories of photovoltaic power, Applied Energy 176 (2016) 80–91.

PV scenarios

- Multivariate random variable $Z = \{Z_1, \ldots, Z_r\}$
- Known quantities:
  - Marginal *cdf*s $F_{Z_i}(\cdot)$, $i = 1, \ldots, r$
  - Correlation matrix R_Z
- **Objective:** generate samples of Z

Method based on Gaussian copula

1: Generate a sample $g = (g_1, \ldots, g_r)$ from a Normal distribution $\mathcal{N}(0, R_Z)$

2: Transform each entry g_i through the standard normal *cdf* $\phi(\cdot)$

$$u_i = \phi(g_i)$$

3: Apply to each entry u_i the inverse marginal *cdf* of Z_i

$$z_i = F_{Z_i}^{-1}(u_i)$$

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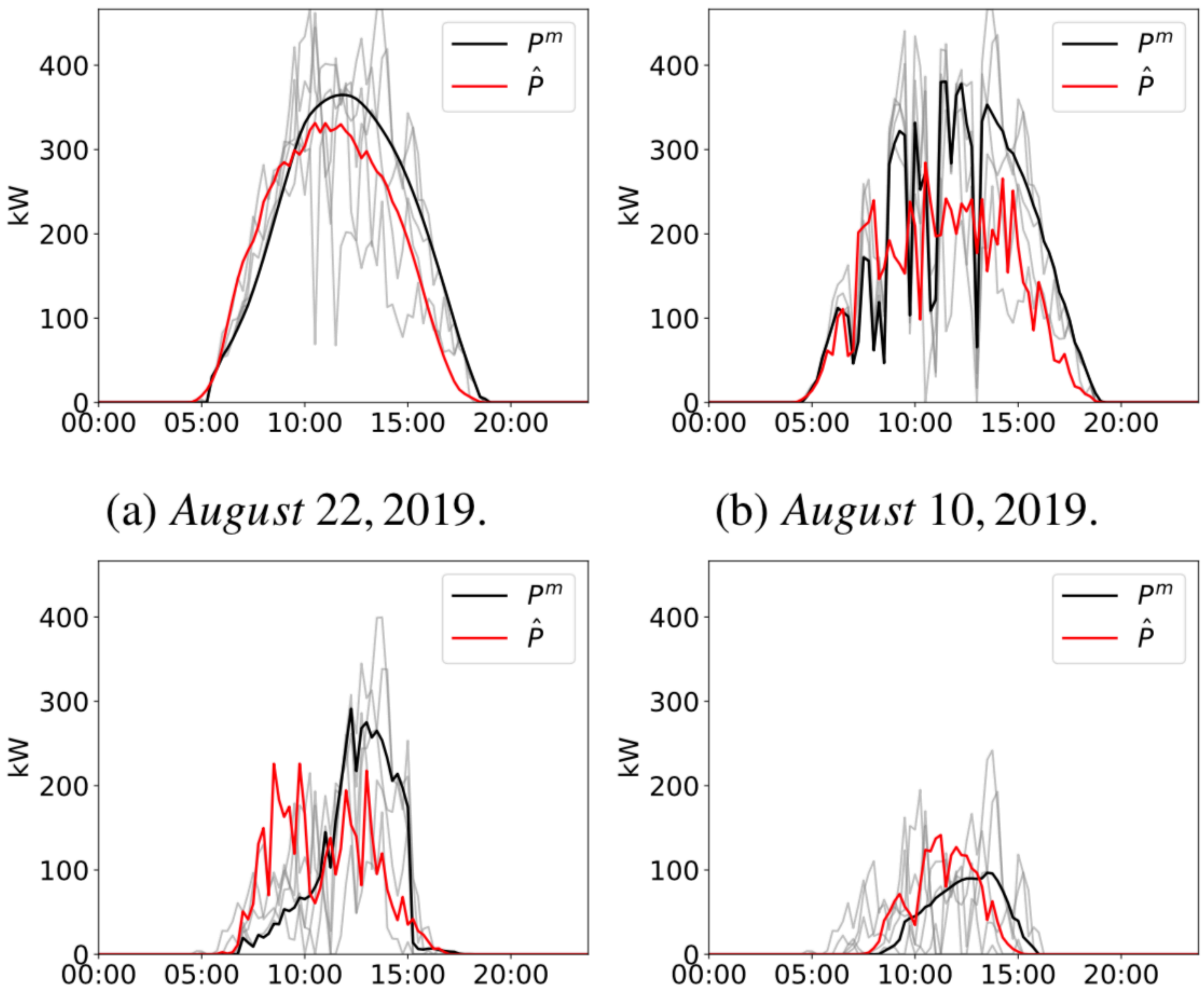
PV scenarios



(a) *August* 22, 2019.

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Figure 5: Set of 5 PV scenarios.

$$\hat{P}_{i,\omega} = \hat{P}_i + z_{i,\omega} \quad i = 1,\ldots,r. \quad (10)$$

Red = PVUSA point forecast

Black = PV measurement

Grey = 5 PV scenarios

NMAE = 4.25 %

NRMSE = 9.20 %

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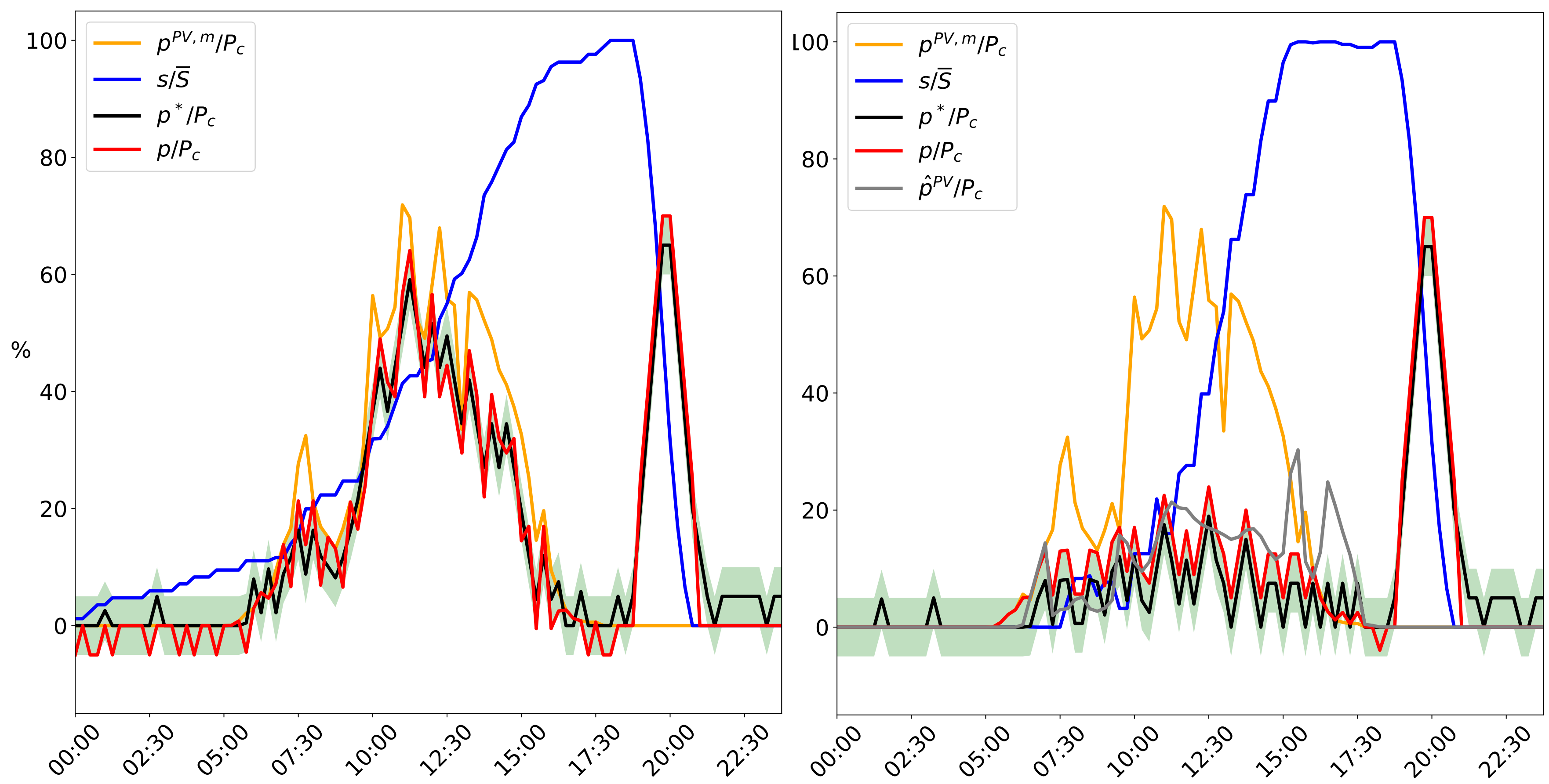
Limitations

The engagement follows the PV point forecasts.



Orange = PV measurement

Blue = state of charge

Black = engagement

Red = production

Gray = PV point forecast

Green = Deadband tolerance

*Figure 7: **D* - oracle** vs **D - oracle** on 12-09-2019.*

Intraday PV point forecast updates are required to compute **re-engagement** plans.