A stochastic optimization model for frequency control and energy management in a microgrid

Dhekra Bousnina (CMA, Mines ParisTech, France)
Welington de Oliveira (CMA, Mines ParisTech, France)
Peter Pflaum (Schneider-Electric, Analytics Applications and Programs, France)

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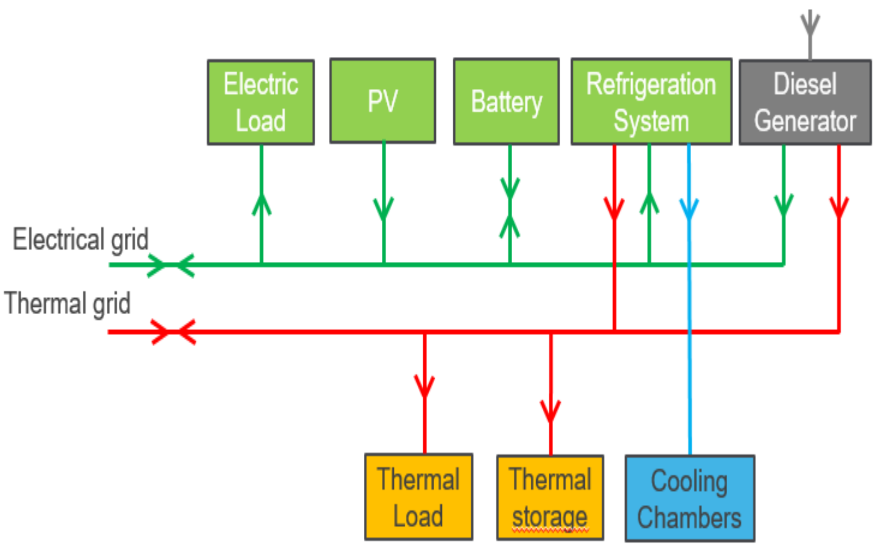
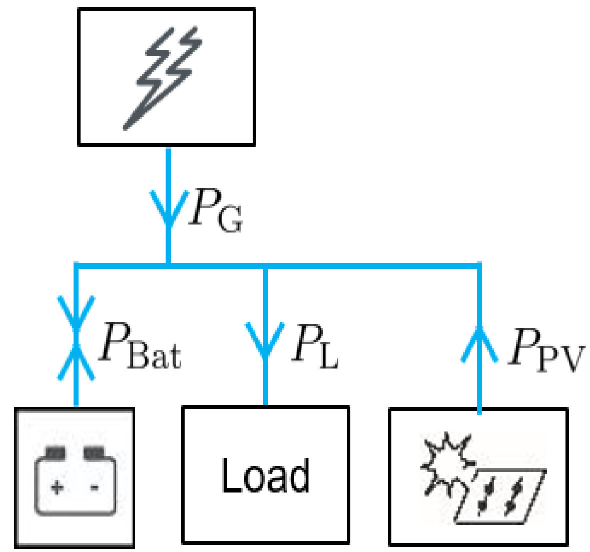
The microgrid system description:

A thermal-electrical microgrid in Finland

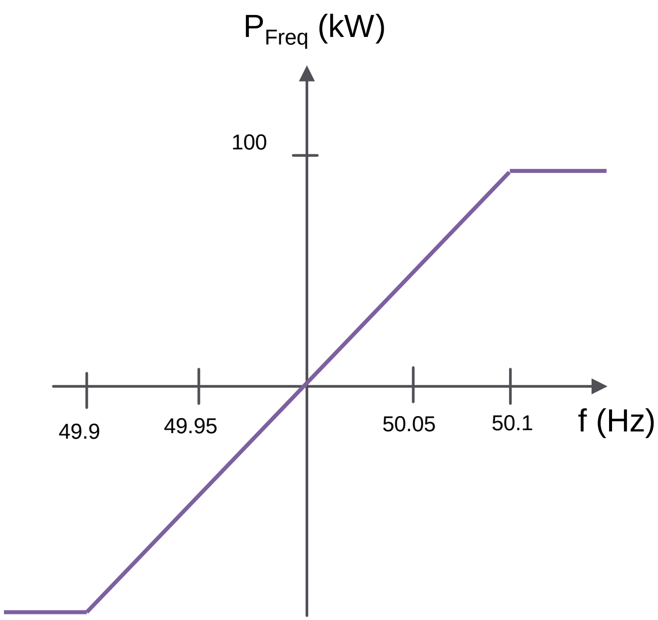
- Participating to the Frequency Containment Reserve market





Frequency Containement Reserve: requirements

- When $\mathbf{P_{produced}} \neq \mathbf{P_{consumed}}$: Frequency of the grid deviated from its nominal value **(50 Hz)**
- Need for frequency regulation to compensate deviations
- Any producer/consumer of a sufficient size **(> 100kW)** can participate in the FCR market



Frequency Containement Reserve: problems

•What is the optimal **day-ahead** frequency **reserve profile** to be submitted ?

What is the the optimal **control strategy for the battery** to minimize energy costs?

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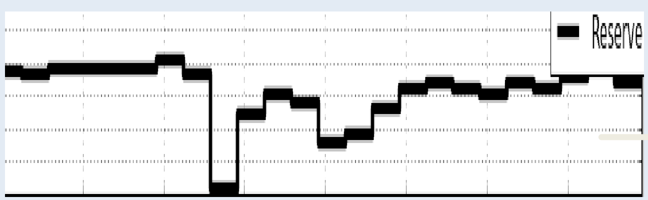
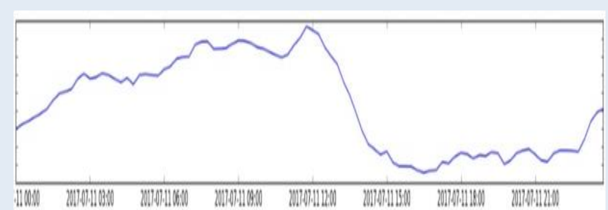
Solve the **planning** optimization problem



Day J-1

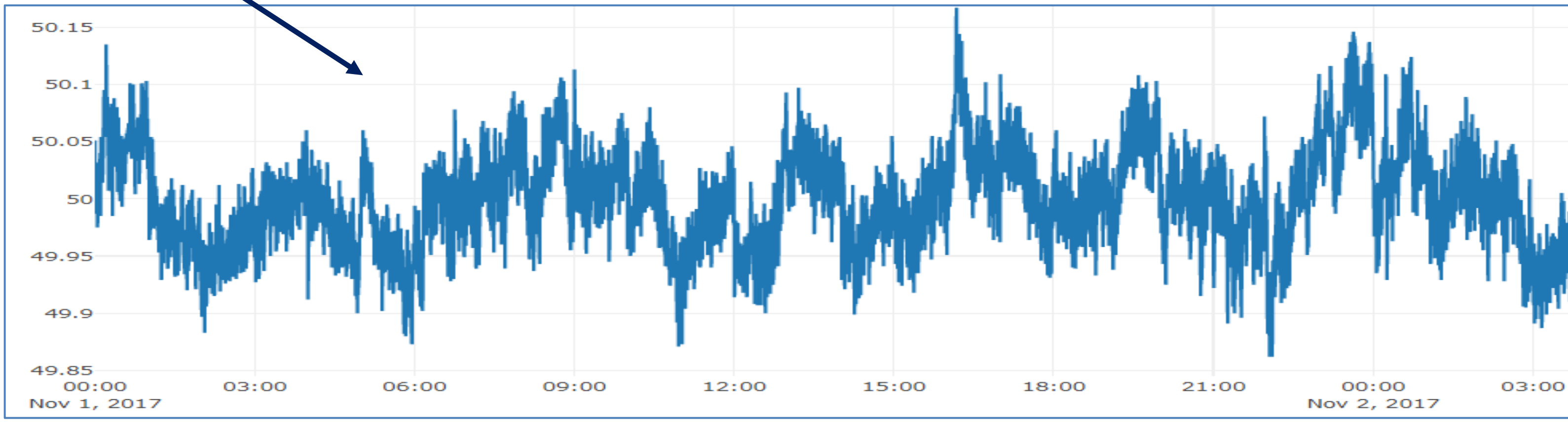
Solve the **control** optimization problem



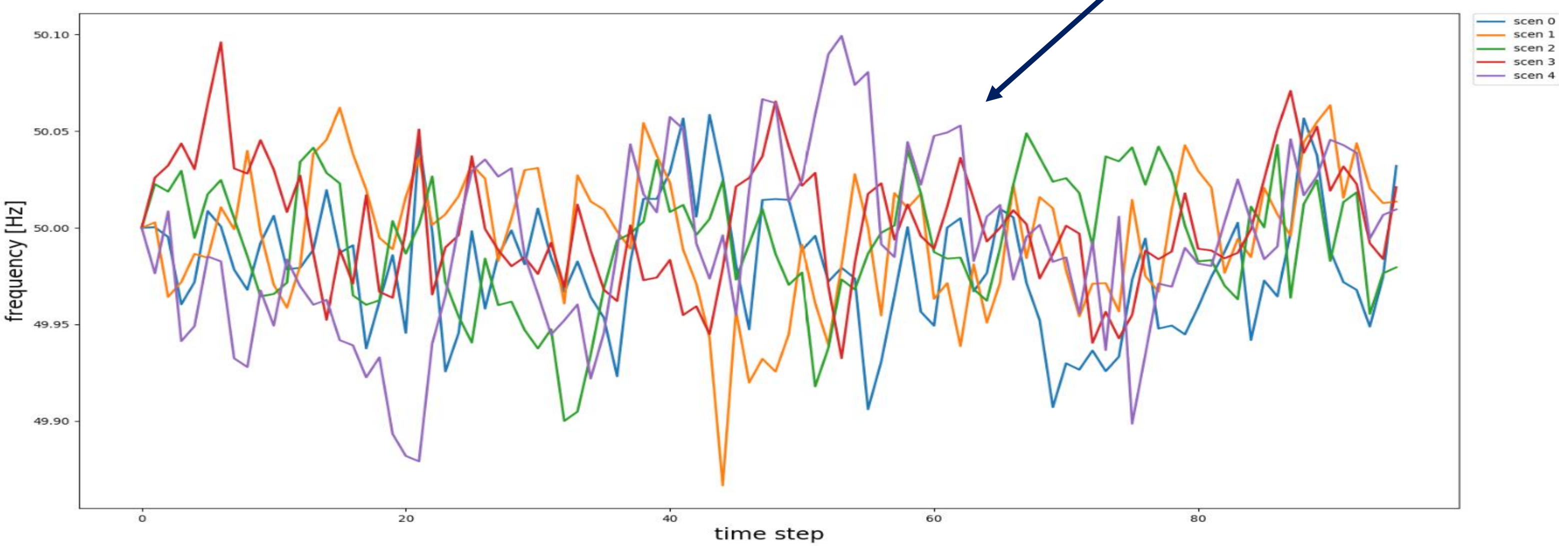
Day J

Frequency Containement Reserve: randomness of frequency deviations

Example of historical frequency deviation realization



Example of 5 generated scenarios using an AR process



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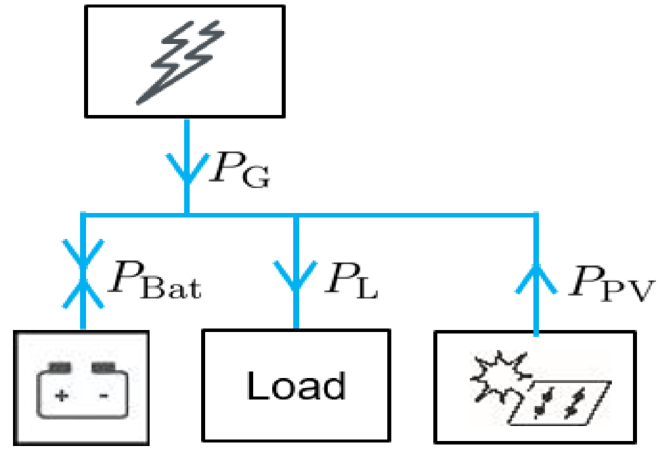
Planning problem: deterministic



$$\min \quad \overbrace{-C_{\mathrm{R}}\sum_{t=0}^{H-1}R_t}^{\text{Revenue from supplied FCR}} + \overbrace{\sum_{t=0}^{H-1}C_{\mathrm{TOU},t}P_{\mathrm{G},t}}^{\text{Energy TOU costs}}$$

$$\begin{aligned}
\text{s.t.} \quad & P_{\mathrm{G},t} = P_{\mathrm{L},t} + P_{\mathrm{B},t} + P_{\mathrm{pv},t} \qquad \forall t && \leftarrow \text{Balance equation}\\
& SoC_{t+1} = SoC_t + P_{\mathrm{B},t}.\Delta t.\eta \qquad \forall t && \leftarrow \text{Battery State of Charge}\\
& P_{\min} + R_t \leq P_{\mathrm{B},t} \leq P_{\max} - R_t \qquad \forall t && \leftarrow \text{Power and energy reserve for frequency regulation}\\
& SoC_{\min} + 0.5R_t \leq SoC_t \leq SoC_{\max} - 0.5R_t \qquad \forall t &&\\
& R_t \geq 0 \qquad \forall t. &&
\end{aligned}$$

Planning problem: stochastic

1

$$
\begin{aligned}
\min \quad & -C_{\mathrm{R}} \sum_{t=0}^{H-1} R_t + \sum_{t=0}^{H-1} C_{\mathrm{TOU},t} P_{\mathrm{G},t} \\
\text{s.t.} \quad & P_{\mathrm{G},t} = P_{\mathrm{L},t} + P_{\mathrm{B},t} + P_{\mathrm{pv},t} \qquad \forall t \\
& SoC_{t+1} = SoC_t + P_{\mathrm{B},t}.\Delta t.\eta \qquad \forall t \\
& P_{\min} + R_t \leq P_{\mathrm{B},t} \leq P_{\max} - R_t \qquad \forall t \\
& SoC_{\min} + 0.5R_t \leq SoC_t \leq SoC_{\max} - 0.5R_t \qquad \forall t \\
& R_t \geq 0 \qquad \forall t.
\end{aligned}
$$

2

$$
\begin{aligned}
\min \quad & -C_{\mathrm{R}} \sum_{t=0}^{H-1} R_t + \boxed{\sum_{t=0}^{H-1} C_{\mathrm{TOU},t} P_{\mathrm{G},t}} \\
\text{s.t.} \quad & P_{\mathrm{G},t} = P_{\mathrm{L},t} + P_{\mathrm{B},t} + P_{\mathrm{pv},t} \qquad \forall t \\
& Soc_{t+1} = \boxed{SoC_t} + P_{\mathrm{B},t}.\Delta t.\eta \qquad \forall t \\
& P_{\mathrm{B},t} = P_{\mathrm{N},t} + R_t \quad \Delta f_t \qquad \forall t \\
& P_{\min} + R_t \leq P_{\mathrm{N},t} \leq P_{\max} - R_t \qquad \forall t \\
& SoC_{\min} + 0.5R_t \leq SoC_t \leq SoC_{\max} - 0.5R_t \qquad \forall t \\
& R_t \geq 0 \qquad \forall t.
\end{aligned}
$$

Random vector

Two-stage stochastic formulation:

$$\min \quad -C_R \sum_{t=0}^{H-1} R_t + \boxed{\sum_{t=0}^{H-1} C_{TOU,t} P_{G,t}}$$

2

$$\begin{aligned}
\text{s.t.} \quad & P_{G,t} = P_{L,t} + P_{B,t} + P_{pv,t} && \forall t \\
& Soc_{t+1} = \boxed{SoC_t} + P_{B,t}.\Delta t.\eta && \forall t \\
& P_{B,t} = P_{N,t} + R_t \; \boxed{\Delta f_t} && \forall t \\
& P_{min} + R_t \le P_{N,t} \le P_{max} - R_t && \forall t \\
& SoC_{min} + 0.5R_t \le SoC_t \le SoC_{max} - 0.5R_t && \forall t \\
& R_t \ge 0 && \forall t.
\end{aligned}$$

3

$$\min \quad -C_R \sum_{t=0}^{H-1} R_t + \mathbb{E}\left[\sum_{t=0}^{H-1} C_{TOU,t} P_{G,t}\right]$$

$$\begin{aligned}
\text{s.t.} \quad & P_{G,t} = P_{L,t} + P_{B,t} + P_{pv,t} && \forall t \\
& Soc_{t+1} = SoC_t + P_{B,t}.\Delta t.\eta && \forall t \\
& P_{B,t} = P_{N,t} + R_t \; \Delta f_t && \forall t \\
& P_{min} + R_t \le P_{N,t} \le P_{max} - R_t && \forall t \\
& SoC_{min} + 0.5R_t \le SoC_t \le SoC_{max} - 0.5R_t && \forall t \\
& R_t \ge 0 && \forall t.
\end{aligned}$$

Replace the term by its expected value

Sample Average Approximation:

3

$$\min \quad -C_R \sum_{t=0}^{H-1} R_t + \mathbb{E}\left[\sum_{t=0}^{H-1} \mathrm{C}_{\mathrm{TOU},t} \mathrm{P}_{\mathrm{G},t}\right]$$

$$\text{s.t.} \quad P_{\mathrm{G},t} = P_{\mathrm{L},t} + P_{\mathrm{B},t} + P_{\mathrm{pv},t} \qquad \forall t$$

$$Soc_{t+1} = SoC_t + P_{\mathrm{B},t}.\Delta t.\eta \qquad \forall t$$

$$P_{\mathrm{B},t} = P_{\mathrm{N},t} + R_t \quad \Delta f_t \qquad \forall t$$

$$P_{\min} + R_t \leq P_{\mathrm{N},t} \leq P_{\max} - R_t \qquad \forall t$$

$$SoC_{\min} + 0.5R_t \leq SoC_t \leq SoC_{\max} - 0.5R_t \qquad \forall t$$

$$R_t \geq 0 \qquad \forall t.$$

4

$$\min \quad -C_R \sum_{t=0}^{H-1} R_t + \frac{1}{\mathrm{N}}\left[\sum_{i=1}^{\mathrm{N}} \sum_{t=0}^{H-1} \mathrm{C}_{\mathrm{TOU},t} \mathrm{P}^{(i)}_{\mathrm{G},t}\right]$$

$$\text{s.t.} \quad P^{(i)}_{\mathrm{G},t} = P_{\mathrm{L},t} + P^{(i)}_{\mathrm{B},t} + P_{\mathrm{pv},t} \qquad \forall i, \forall t$$

$$SoC^{(i)}_{t+1} = SoC^{(i)}_t + P^{(i)}_{\mathrm{B},t}.\Delta t.\eta \qquad \forall i, \forall t$$

$$P^{(i)}_{\mathrm{B},t} = P^{(i)}_{\mathrm{N},t} + R_t \Delta f^{(i)}_t \qquad \forall i, \forall t$$

$$P_{\min} + R_t \leq P^{(i)}_{\mathrm{N},t} \leq P_{\max} - R_t \qquad \forall i, \forall t$$

$$SoC_{\min} + 0.5R_t \leq SoC^{(i)}_t \leq SoC_{\max} - 0.5R_t \qquad \forall i, \forall t$$

$$R_t \geq 0 \qquad \forall t.$$

Averaged value on N scenarios

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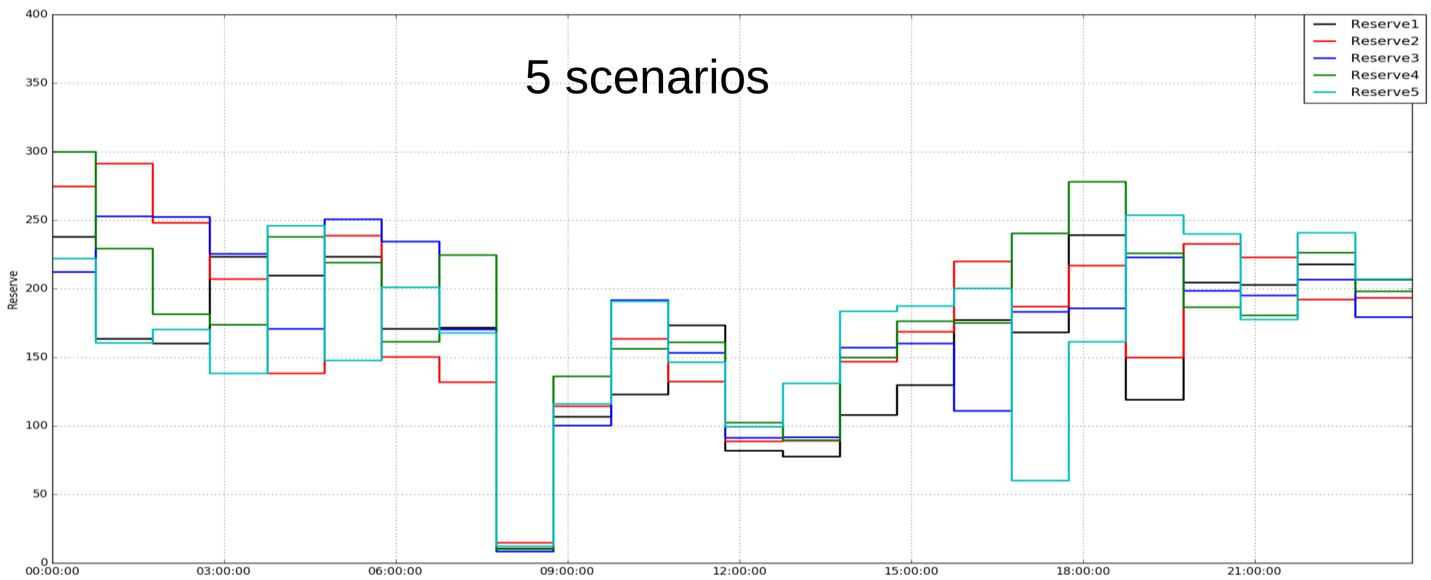
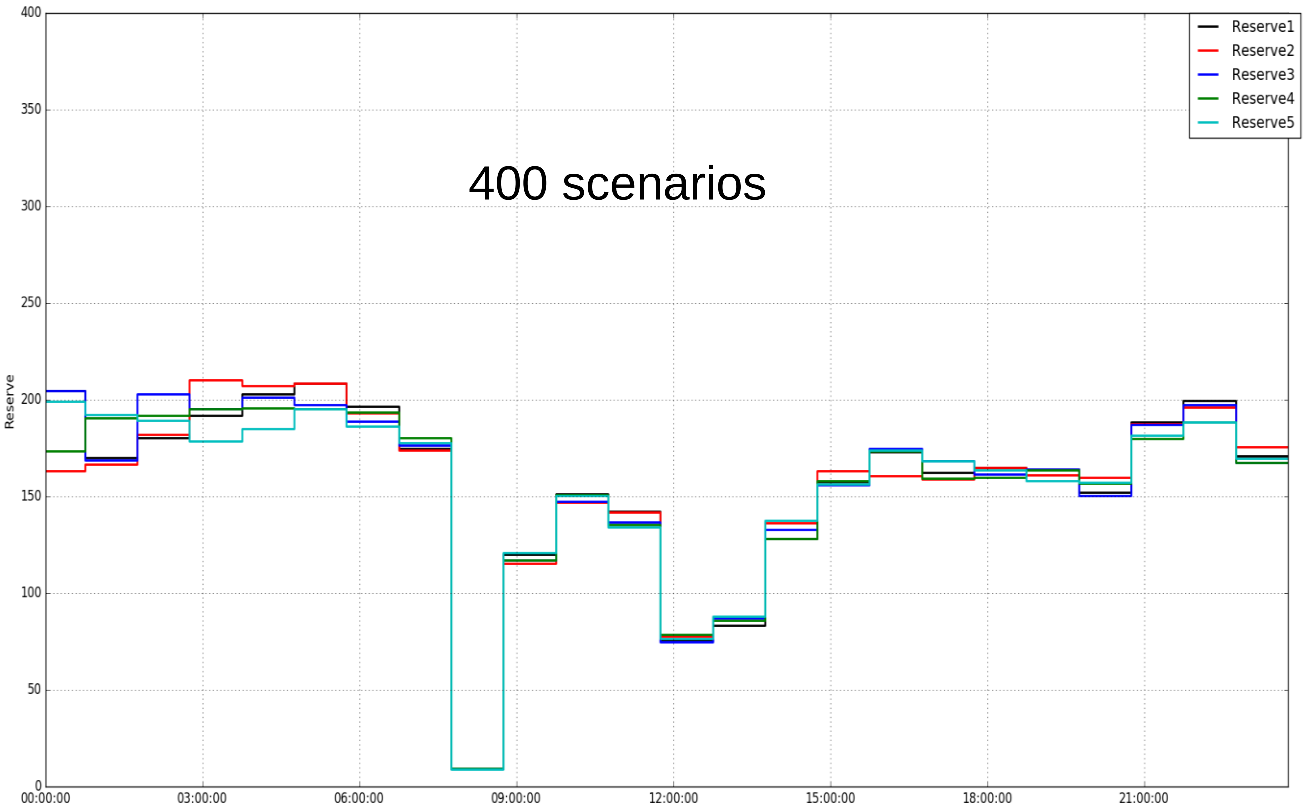
Impact of the number of scenarios:

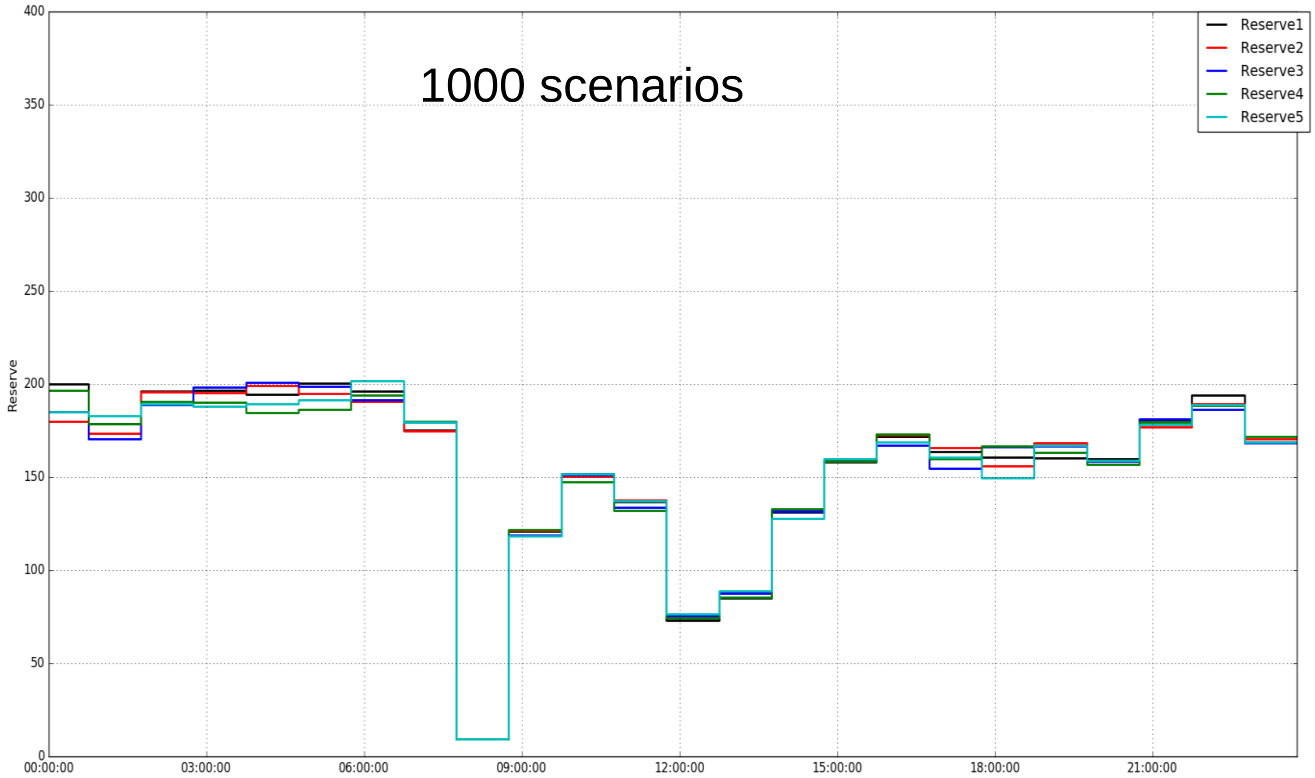
- **Solve the planning problem several times with different numbers of scenarios (**N=5, 400, 1000)



Impact of the number of scenarios:



Impact of the number of scenarios:



Out-of-sample simulations:

Solve several times the same **planning problem** 1

N = 5

5 reserve profiles with N=5

N = 400

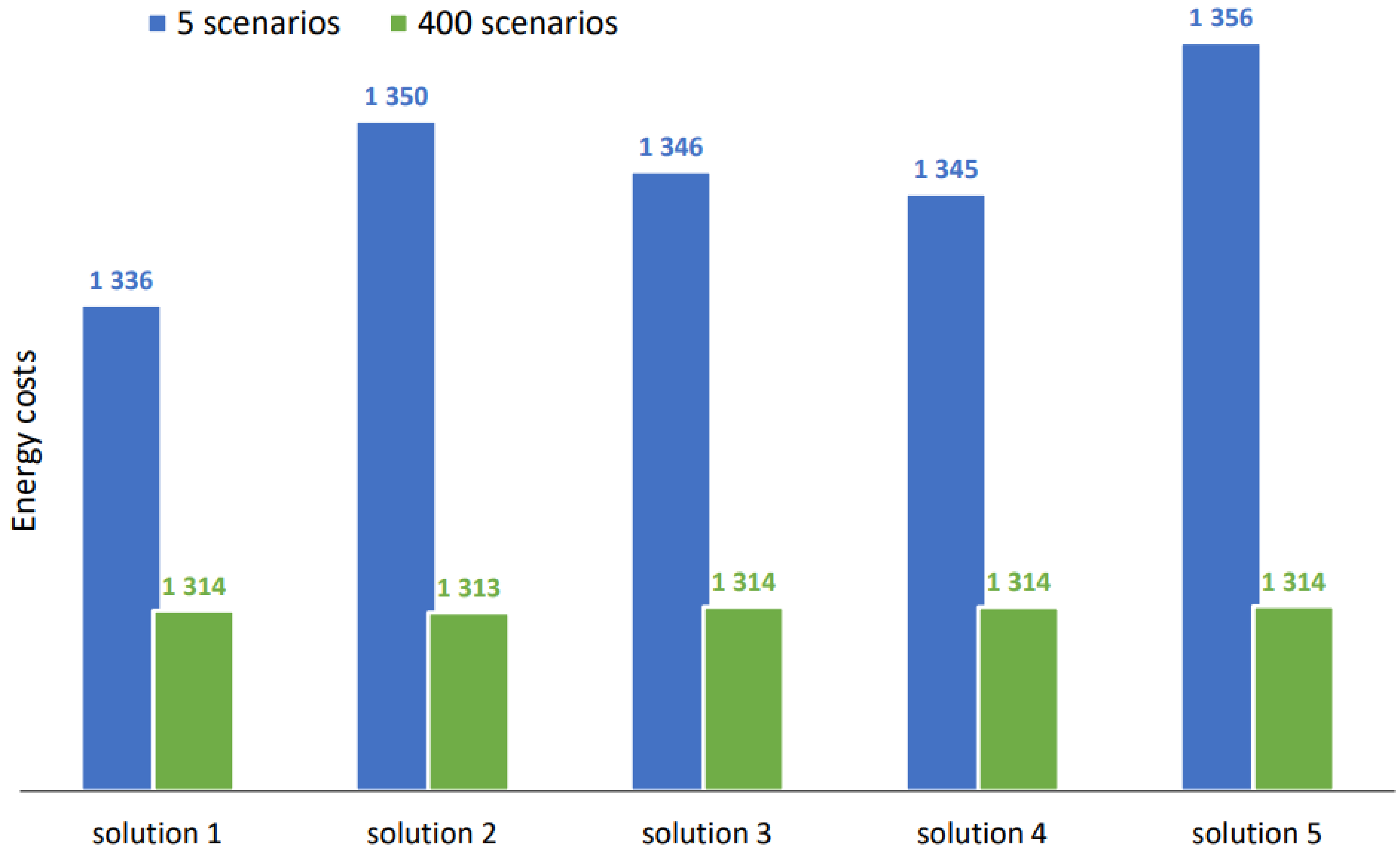
5 reserve profiles with N=400

Generate another independent sample of **1000 scenarios** 2

Solve 1000 variants of the **control problem for each of the 10 reserve profiles** 3

Compute the **average** of the 1000 obtained costs 4

Out-of-sample simulations:



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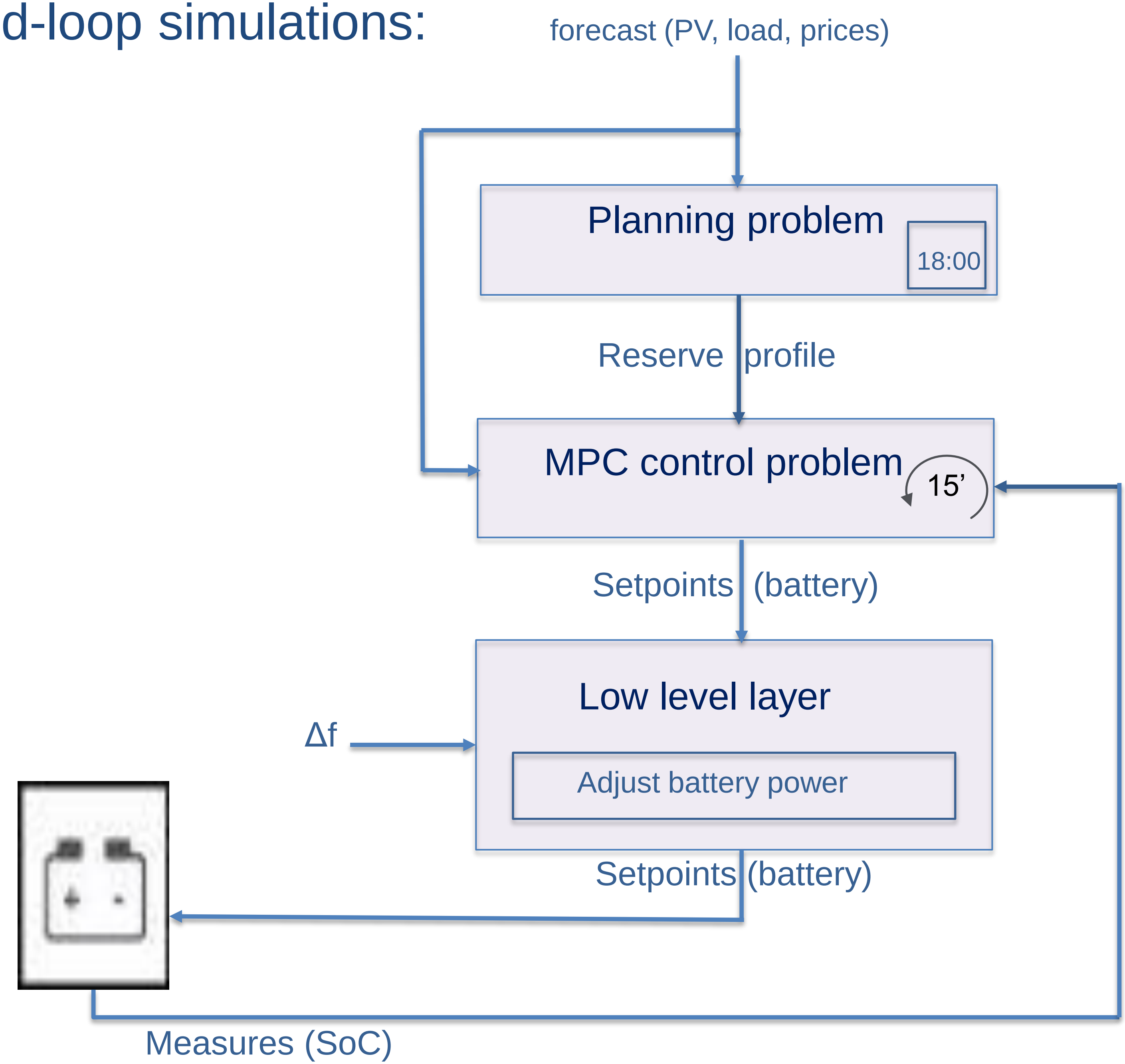
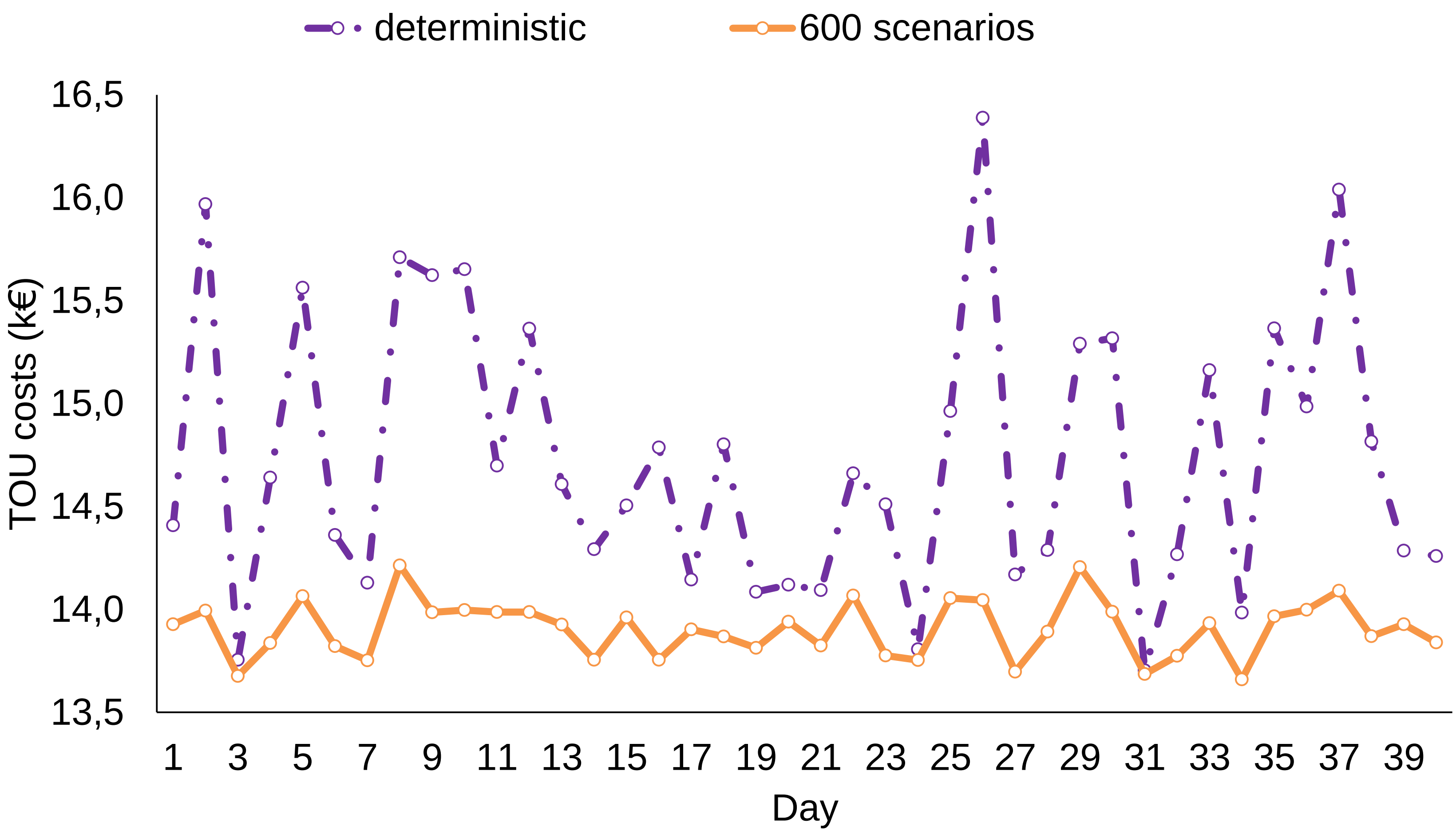
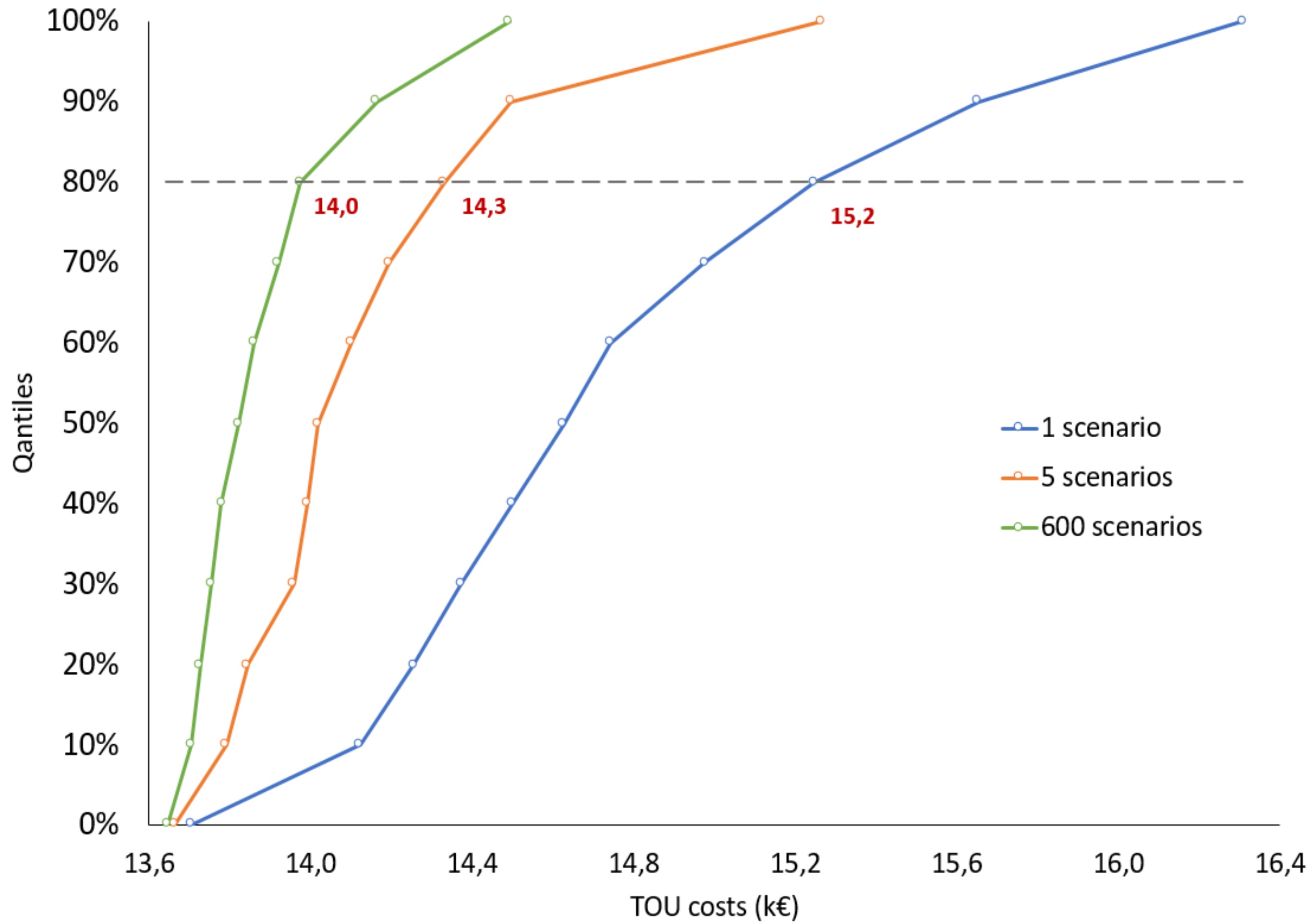
Closed-loop simulations:



Closed-loop simulations: deterministic VS stochastic:



Closed-loop simulations: impact of the number of scenarios



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Conclusion

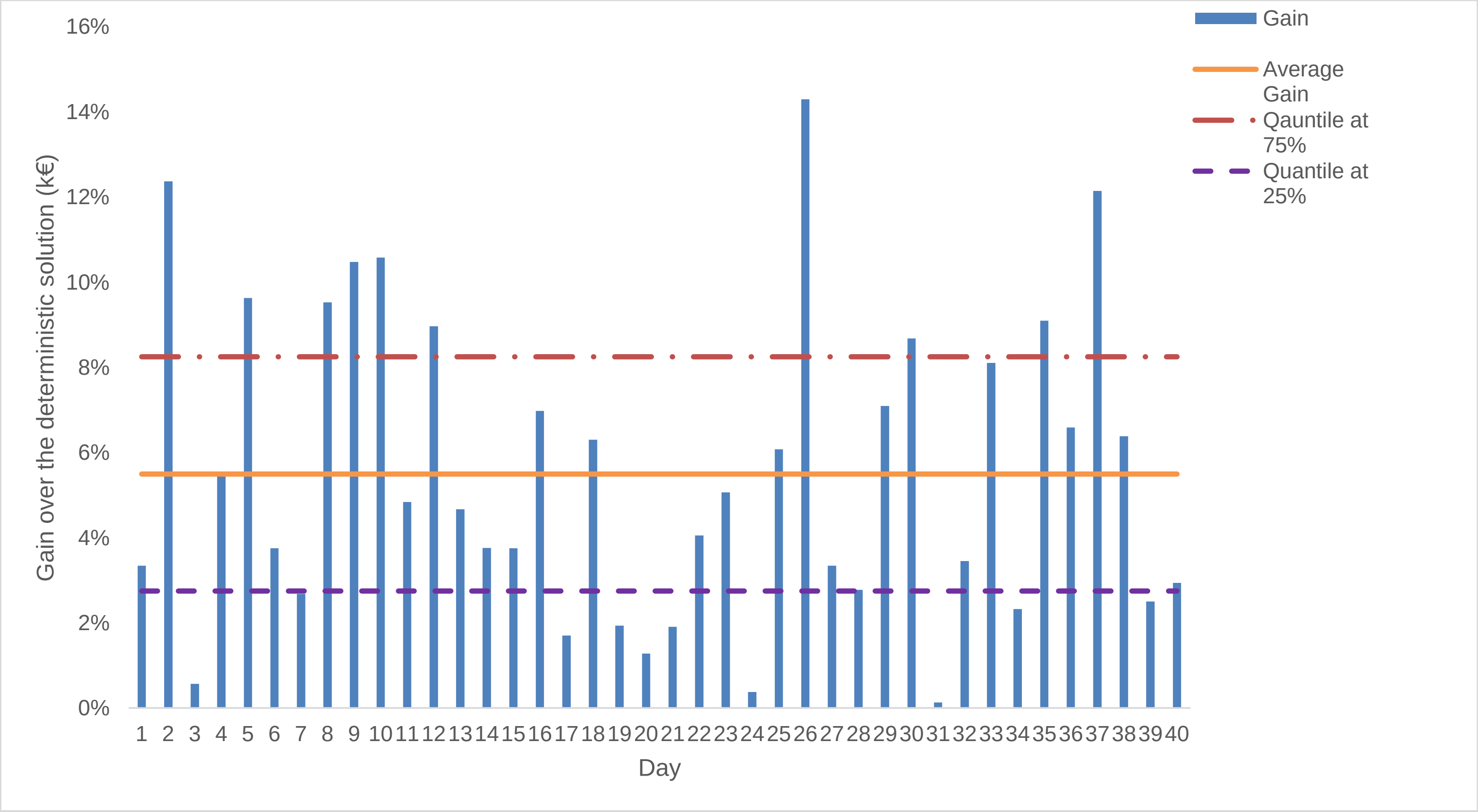
- Development of a stochastic programming approach to deal with the uncertainty in FCR
- Comparison with a classical/ deterministic approach
- Stochastic programming: reduced energy costs, reduced risks and a better predictability

Future work

- **Reducing the computational time** (decomposition/ clustering/ scenario reduction techniques…)
- **Considering other sources of uncertainty** (load, PV production, electricity prices…)
- **Extending to muli-energy optimization** (thermal and electrical)

Thank you for your attention

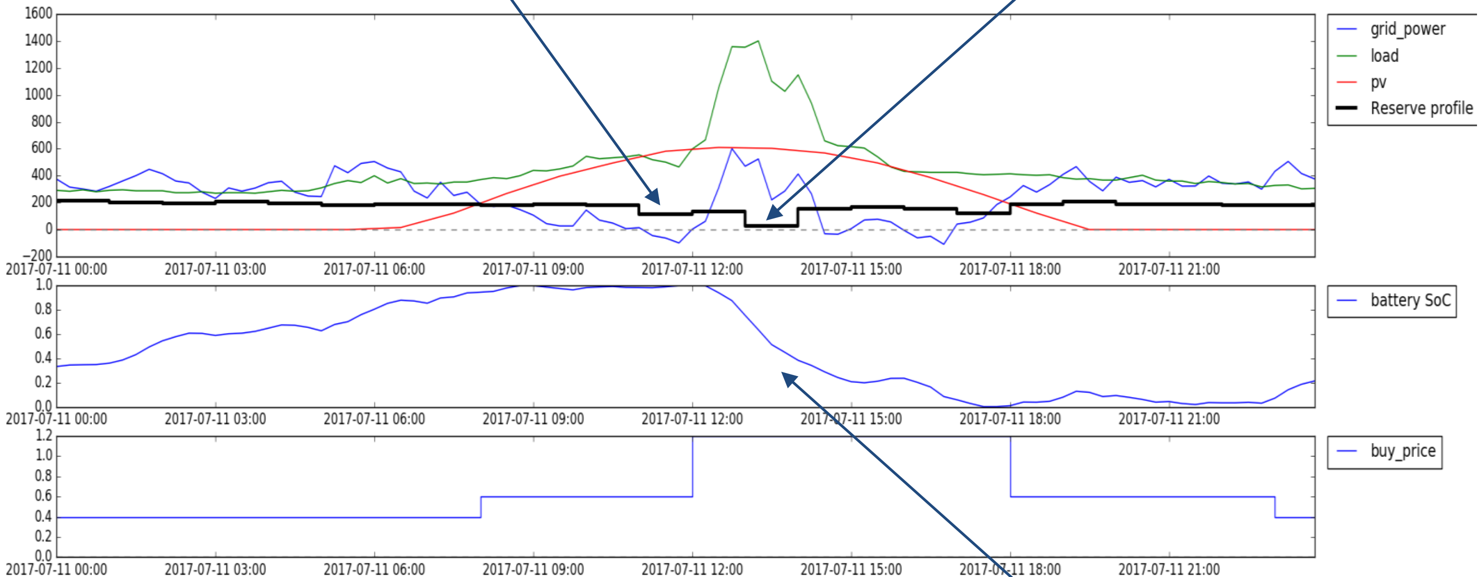
Closed-loop simulations: deterministic VS stochastic:



Closed-loop simulations: overview of the results

Provide less frequency reserve to store surplus PV

No FCR reserve: battery used only for self-consumption



Discharging the battery during high price periods