Energy Management Systems and Demand Response

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Goals

- For a toy power mix problem, to compare the pros and cons of implementing a demand-response mechanism by considering:
  a) Load-shaving constraints
  b) Energy-management system depending on a battery

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- The inclusion of a third objective, aiming at maximizing the battery life, could also be important to take into account .

MATHEMATICAL FORMULATION

Mathematical Formulation

- N utilities K_j and T time steps
- Cost c_j of the energy generated by utility K_j
- CO_2 emission E_j from utility K_j
- g_j^t power generated by utility K_j at time t
- Technological constraints for generated power g_j^t in G_j^t (affine set)
- Customers' demand d^t at time t

$$\text{minimize} \quad \left(\sum_{j=1}^{N} \sum_{t=1}^{T} c_j g_j^t , \ \sum_{j=1}^{N} \sum_{t=1}^{T} E_j g_j^t \right)$$

$$\text{subject to} \quad g_j^t \in G_j^t, \ j = 1, \dots, N, \ t = 1, \dots, T$$

$$\sum_{j=1}^{N} g_j^t = d^t, \ t = 1, \dots, T$$

Load-shaving

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Model

$$
\begin{aligned}
&-\gamma \le x^t \le v^t \le \gamma, && t = 1, \dots, T, \\
&v^t \ge 0 && t = 1, \dots, T, \\
&\sum_{t=1}^{T} x^t = 0, \sum_{t=1}^{T} v^t \le \gamma, &&
\end{aligned}
$$

- x^t is the displaced energy at time t
- v^t is the maximum power that can be displaced at each period
- γ is a bound for the power that can be shifted along the planning horizon

Energy Management System

Along the lines of

- B. Heymann, P. Martinon, F. Silva, F. Lanas, G. Jiménez, e J.F. Bonnans.*Continuous Optimal Control Approaches to Microgrid Energy Management*. `https://hal.inria.fr/hal-01129393`, 2015.

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The battery can store energy for later use, but has a limited capacity and power.

Energy Management System

- Variables
  - y^t: state of charge of the battery at time t
  - P_I^t and P_O^t: input and output power of the battery at time t
- Parameters
  - Q_B: maximum capacity of the battery
  - $\rho_I,\ \rho_O \in [0,1]$: efficiency ratios for the charge and discharge processes
  - y^{min} and y^{max}: minimum and maximum of the state of charge of the battery
  - P_I^{max} and P_O^{max}: maximum input and output power of the battery

Energy Management System Constraints

$$y^{t+1} - y^t = \frac{1}{Q_B}\left(P_I^t \rho_I - \frac{P_O^t}{\rho_O}\right)$$

$$\begin{cases} P_I^t \in [0, P_I^{max}] & \text{if } y^t < 0.9 \\ P_I^t \leq 100 P_I^{max}(y^t - 1)^2 & \text{otherwise} \end{cases}$$

$$P_O^t \in [0, P_O^{max}], \quad y^1 = y^T$$

$$\sum_{j=1}^{N} g_j^t + P_O^t - P_I^t = d^t$$

$$P_O^t = -\min\left\{0, \sum_{j=1}^{N} g_j^t - d^t\right\}$$

$$P_I^t = \max\left\{0, \sum_{j=1}^{N} g_j^t - d^t\right\}$$

for $t = 1, \ldots, T$,

MULTI-OBJECTIVE OPTIMIZATION

Multi-objective problem (MOP)

$$\begin{array}{ll} \text{minimize} & f(x) = (f_1(x), \ldots, f_s(x)) \\ \text{subject to} & x \in Q \end{array}$$

- $x^* \in Q$ is a **Pareto solution** if there exists no $x \in Q$ such that $f(x) \neq f(x^*)$ and

$$f_i(x) \leq f_i(x^*), \qquad \text{for all } i = 1, \cdots, s.$$

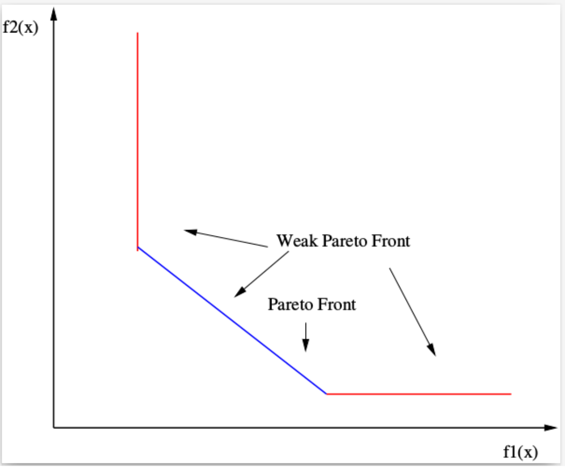
- $x^* \in Q$ is a **weak Pareto solution** if there exists no $x \in Q$ such that

$$f_i(x) < f_i(x^*), \qquad \text{for all } i = 1, \cdots, s.$$

- Set of Pareto and weak Pareto solutions: P and P_w
- Pareto and weak Pareto front:

$$\mathcal{F} = \{f(x) \mid x \in P\}, \qquad \mathcal{F}_w = \{f(x) \mid x \in P_w\}$$

Example: Pareto and weak Pareto Front



Multi-objective programming solution method

- C.Y. Kaya and H. Maurer. *A Numerical Method for Nonconvex Multi-Objective Optimal Control Problems.* Comput Optim Appl, 57: 685-702, 2014.

Single objective problem P_i

$$\begin{array}{ll} \text{Minimize} & f_i(x) \\ \text{suject to:} & x \in Q \end{array}$$

- Denote x_i^* a solution of (P_i) and $f_i^* = f_i(x_i^*)$.
- Define a *utopian objective vector* β^*

$$\beta_i^* = f_i^* - \varepsilon_i$$

where $\varepsilon_i > 0$ for all $i = 1, \cdots, s$.

Scalarization

Weighted Chebyshev problem (MOP$_w$)

$$\begin{array}{ll} \text{minimize} & \max\limits_{i=1,\dots,s} w_i(f_i(x) - \beta_i^*) \\ \text{subject to} & x \in Q \end{array}$$

where $w_i \geq 0,\ i = 1, \dots, s$ and $\sum_{i=1}^{s} w_i = 1$.

Theorem [J. Jahn, Corollary 5.35]

A vector $x^* \in Q$ is a weak Pareto minimum of (MOP) if, and only if, $x^* \in Q$ is a solution of (MOP$_w$) for some $w_1, \cdots, w_s > 0$.

Multi-objective programming solution method

Problem (MOP_w) is a non-smooth optimization problem, because of the max operator in the objective. So it is re-formulated as:

Smooth form of (MOP_w)

$$
\begin{aligned}
\text{minimize} \quad & \alpha \\
\text{subject to} \quad & \alpha \geq 0 \\
& x \in Q \\
& w_1(f_1(x) - \beta_1^*) \leq \alpha, \\
& \vdots \\
& w_s(f_s(x) - \beta_s^*) \leq \alpha
\end{aligned}
$$

Algorithm by Kaya and Maurer, Comput Optim Appl, 2014

Data: ε_1, $\varepsilon_2 > 0$, $(N+1)$ number of discretization points

$k = 1$

Compute the boundary of the Pareto front: $(f_1^*, f_2(x_1^*))$, $(f_1(x_2^*), f_2^*)$

Parameters: $\beta_i^* = f_i^* - \varepsilon_i, \; i = 1, 2,$

Initial weights: w_0, w_f, Δw

REPEAT while $k < N$

- Set the current weights $w = w_0 + k\Delta w$, $w_1 = w$ and $w_2 = 1 - w$
- Find a Pareto minimun x^* that solves Problem (MOP_w)
- Assign a point in the Pareto front: $\bar{f}^k = (f_1(x^*), f_2(x^*))$
- $k = k + 1$

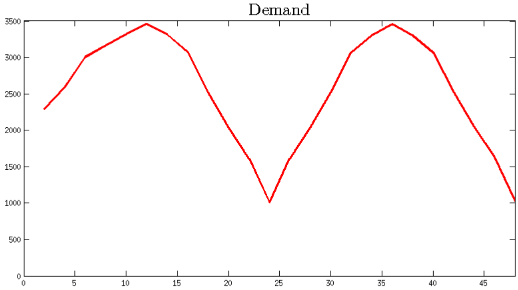
NUMERICAL RESULTS

Numerical Results

- 9 thermal power plants (3 nuclear, 2 coal, 3 gas and 1 combustion turbine)
- Solar energy g_S^t generated by the relation:

$$s^t = 75 \max\left(\sin\left(\frac{(t-4)\pi}{5}\right), 0\right)$$

- Time horizon of 48 hours discretized in 2h time steps



Numerical Results

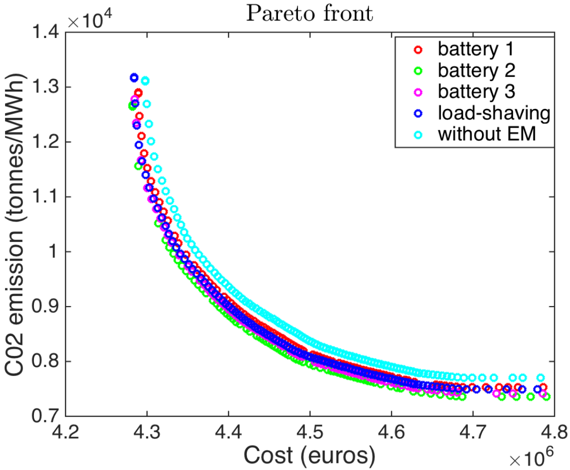
- Maximum of power that we can displaced at load-shaving

$$\gamma = 100 \text{ Megawatts.}$$

- Three instances, with different configurations for the battery:
  - **Battery one**: $Q_B = 117$, $P_I^{max} = 13.2$ and $P_O^{max} = 40$.
  - **Battery two**: $Q_B = 234$, $P_I^{max} = 26.4$ and $P_O^{max} = 80$.
  - **Battery three**: $Q_B = 200$, $P_I^{max} = 13.2$ and $P_O^{max} = 40$.

Numerical Results

Number of discretization points $N = 100$



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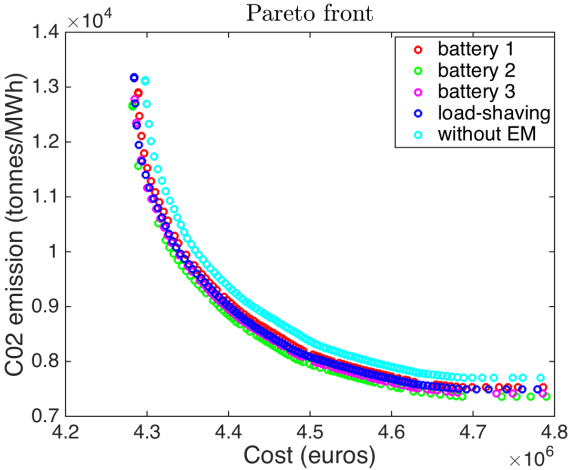
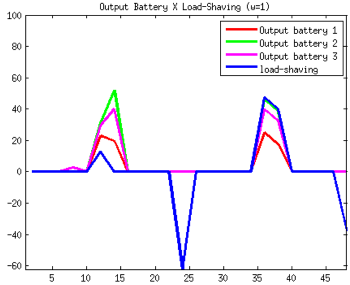
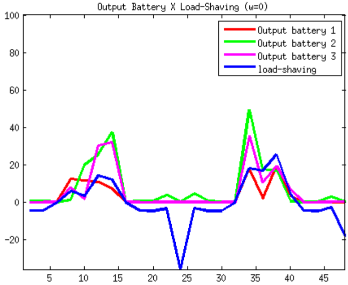
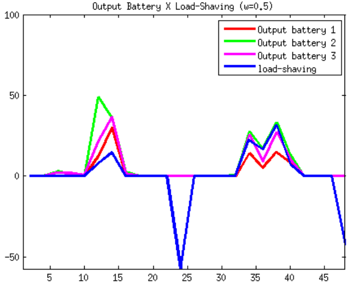


- Best option: battery 2.

Load-shaving and Battery storage: similar behaviour







Conclusions

- Both mechanisms, load-shaving and an EMS, have a positive effect on demand response. We observe a reduction in generation cost and carbon emission.
- If the battery is sufficiently large, the results are better than load-shaving.

Future Steps

a) In discrete time,develop a dedicated bundle method combining achievement and improvement functions, exploiting warm starts to generate the Pareto front (ongoing work).

b) In continuous time: solve the HJB formulation (without DR, that couples all time steps) and compare with **a)**.

c) Include frequency control at peak times.

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Merci de votre attention