Decentralized Energy Management: Two Examples

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Goals of the lecture

- Present two examples in energy management:
  - distributed production,
  - demand response,

  as well as different schemes to manage them.

- Open the discussion for solving these problems.

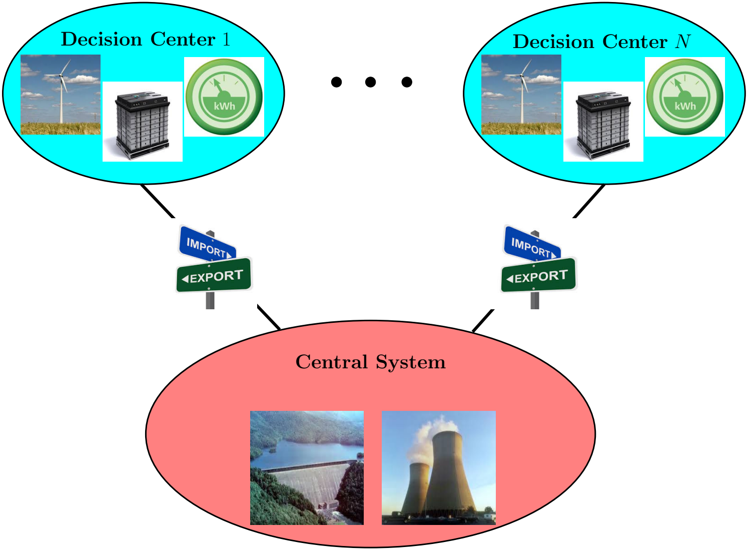
Lecture outline

1. First Example: Distributed Production
    - Modelling the Problem
    - Centralized Management
    - Leader-Follower Approach

2. Second Example: Demand Response
    - Demand and Procurement Models
    - Shedding Strategy

3. Conclusions and Open Questions

Schematic View



Production Problem

Work based on the internship of Y. Ameur [Ameur, 2013].

In this first example, we consider N_{dc} independent decision centers connected through a central system.

- Each Decision Center ($\mathbf{DC}_i$)
  - has different energy production capacities (wind, thermal...),
  - is able to store energy (battery),
  - may import energy from the central system.
- The Central System (**CS**)
  - incorporates nuclear plants and large dams,
  - has to buy (a part of) the fatal energy production,
  - provides energy to the decision centers.

The problem is formulated on a discrete time horizon $\{0, \ldots, T\}$.

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Decision Center Model

The decision center $\mathbf{DC}_i$ consists of the following elements

- a non controlled demand $\boldsymbol{D}_{i,t}$ (random perturbation),
- a fatal wind production $\boldsymbol{W}_{i,t}$ (random perturbation),
- a fossil production: control $\boldsymbol{U}^g_{i,t}$ with cost term $\alpha^g_i \big(\boldsymbol{U}^g_{i,t}\big)^2$,
- a dispatchable load: control $\boldsymbol{U}^l_{i,t}$, state $\boldsymbol{X}^l_{i,t}$ governed by

$$\boldsymbol{X}^l_{i,0} = 0, \quad \boldsymbol{X}^l_{i,t+1} = \boldsymbol{X}^l_{i,t} + \boldsymbol{U}^l_{i,t}, \quad \boldsymbol{U}^l_{i,t} \geq 0 ,$$

  with cost term $\alpha^l_i \big(\boldsymbol{X}^l_{i,T} - \overline{x}^l_i\big)^2$,
- a battery: control $\boldsymbol{U}^b_{i,t}$, state $\boldsymbol{X}^b_{i,t}$ governed by

$$\boldsymbol{X}^b_{i,0} = x^b_{i,0}, \quad \boldsymbol{X}^b_{i,t+1} = \boldsymbol{X}^b_{i,t} + \boldsymbol{U}^b_{i,t} ,$$

  with cost term $\alpha^b_i \big(\boldsymbol{X}^b_{i,t} - \widetilde{x}^b_i\big)^2$.

Decision Center Model II

There is an energy exchange with the central system, that is,

- an export production $\boldsymbol{U}^{\mathrm{exp}}_{i,t}$ at a fixed price p^{oa}, with

$$\boldsymbol{U}^{\mathrm{exp}}_{i,t} \leq \boldsymbol{W}_{i,t} \ ,$$

  (purchase by **CS** of all or part of the fatal energy),

- an import production $\boldsymbol{U}^{\mathrm{imp}}_{i,t}$ (possible energy supply from the central system).

The flow balance equation for the decision center i writes

$$\boldsymbol{D}_{i,t} + \boldsymbol{U}^{l}_{i,t} + \boldsymbol{U}^{b}_{i,t} + \boldsymbol{U}^{\mathrm{exp}}_{i,t} \leq \boldsymbol{W}_{i,t} + \boldsymbol{U}^{g}_{i,t} + \boldsymbol{U}^{\mathrm{imp}}_{i,t} \ .$$

Decision Center Model III

We denote by $\boldsymbol{U}_i = \big(\boldsymbol{U}^l_{i,t}, \boldsymbol{U}^g_{i,t}, \boldsymbol{U}^b_{i,t}, \boldsymbol{U}^{\mathrm{imp}}_{i,t}, \boldsymbol{U}^{\mathrm{exp}}_{i,t}\big)_{t=0,\dots,T-1}$ the vector of controls available for $\mathbf{DC}_i$.

The inner operating cost of the decision center i is denoted

$$J_i(\boldsymbol{U}_i) = \sum_{t=0}^{T-1} \Big(\alpha^g_i \big(\boldsymbol{U}^g_{i,t}\big)^2 + \alpha^b_i \big(\boldsymbol{X}^b_{i,t} - \overline{x}^b_i\big)^2 - p^{\mathrm{oa}} \boldsymbol{U}^{\mathrm{exp}}_{i,t}\Big) + \alpha^l_i \big(\boldsymbol{X}^l_{i,T} - \overline{x}^l_i\big)^2 ,$$

and there are many constraints (supply-demande balance, bounds, dynamics, measurability).

Central System Model

The central system **CS** encompasses:

- a non control demand $\boldsymbol{D}_t$ (random disturbance),
- N_{nuc} plants: plant j produces $\boldsymbol{U}^n_{j,t}$ (control) at price p^{n}_j,
- N_{dam} dams: dam k produces energy $\boldsymbol{U}^d_{k,t}$ at no cost, and its state $\boldsymbol{X}^d_{k,t}$ is governed by the dynamics:

$$\boldsymbol{X}^d_{k,0} = x^d_{k,0} , \quad \boldsymbol{X}^d_{k,t+1} = \boldsymbol{X}^d_{k,t} - \boldsymbol{U}^d_{k,t} + \boldsymbol{W}^d_{k,t} ,$$

  where $\boldsymbol{W}^d_{k,t}$ is the random inflow received by dam k.
- an energy exchange with the centers; the central system
  - buys the energy $\boldsymbol{U}^{\mathrm{exp}}_t$ exported by the decisions centers (p^{oa}),
  - furnishes the amount of energy $\boldsymbol{U}^{\mathrm{imp}}_t$ to the decisions centers.

Central System Model II

The flow balance equation for the central system is given by

$$\sum_{j=1}^{N_{\mathrm{nuc}}} \boldsymbol{U}^n_{j,t} + \sum_{k=1}^{N_{\mathrm{dam}}} \boldsymbol{U}^d_{k,t} + \boldsymbol{U}^{\mathrm{exp}}_t \geq \boldsymbol{D}_t + \boldsymbol{U}^{\mathrm{imp}}_t \ .$$

Let $\boldsymbol{U} = \Big(\{\boldsymbol{U}^n_{j,t}\}_{j=1\ldots N_{\mathrm{nuc}}}, \{\boldsymbol{U}^d_{k,t}\}_{k=1\ldots N_{\mathrm{dam}}}, \boldsymbol{U}^{\mathrm{imp}}_t, \boldsymbol{U}^{\mathrm{exp}}_t\Big)_{t=0\ldots T-1}$ be the set of controls associated to the central system.

We denote by $J(\boldsymbol{U})$ the inner operating cost of the central system:

$$J(\boldsymbol{U}) = \sum_{t=0}^{T-1} \Bigg(\sum_{j=1}^{N_{\mathrm{nuc}}} p^{\mathrm{n}}_j \boldsymbol{U}^n_{j,t} \Bigg) + \sum_{t=0}^{T-1} p^{\mathrm{oa}} \boldsymbol{U}^{\mathrm{exp}}_t \ .$$

Problem Coupling

The coupling between the central system and the decision centers arises from the exchange balance, that is,

$$\boldsymbol{U}_t^{\mathrm{exp}} - \sum_{i=1}^{N_{\mathrm{dc}}} \boldsymbol{U}_{i,t}^{\mathrm{exp}} = 0 \quad , \quad \sum_{i=1}^{N_{\mathrm{dc}}} \boldsymbol{U}_{i,t}^{\mathrm{imp}} - \boldsymbol{U}_t^{\mathrm{imp}} = 0 \; .$$

Goals: *explore different ways to pose an optimization problem associated to the management of the overall system (decision centers and central system), and identify prices* $\boldsymbol{P}$ *related to the energy import by the decision centers.*

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Standard Optimization Point of View I

Here we consider that a unique decision maker solves the overall system. In this setting, the problem writes

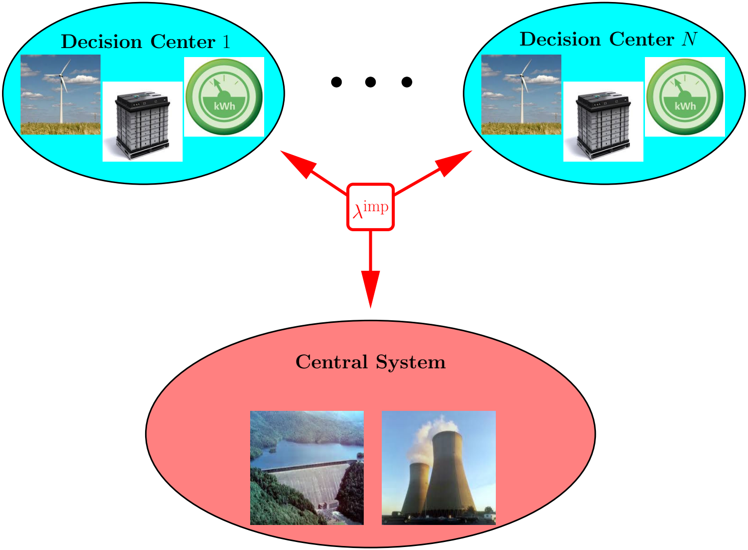
$$\min_{\boldsymbol{U},\boldsymbol{U}_1,\dots,\boldsymbol{U}_{N_{\mathrm{dc}}}} \quad \mathbb{E}\bigg(J(\boldsymbol{U}) + \sum_{i=1}^{N_{\mathrm{dc}}} J_i(\boldsymbol{U}_i) \bigg) ,$$

subject to all local constraints and to the coupling constraints

$$\boldsymbol{U}_t^{\mathrm{exp}} - \sum_{i=1}^{N_{\mathrm{dc}}} \boldsymbol{U}_{i,t}^{\mathrm{exp}} = 0 \quad , \quad \sum_{i=1}^{N_{\mathrm{dc}}} \boldsymbol{U}_{i,t}^{\mathrm{imp}} - \boldsymbol{U}_t^{\mathrm{imp}} = 0 \; .$$

These contraints may be dualized using multipliers denoted by $\boldsymbol{\lambda}_t^{\mathrm{exp}}$ and $\boldsymbol{\lambda}_t^{\mathrm{imp}}$. This leads to an iterative process involving a subproblem for the central system and a subproblem for each decision center.

Decomposition/Coordination Scheme



Subproblems and Prices

Decision Center subproblems

$$\min_{\boldsymbol{U}_i} \mathbb{E}\bigg(J_i(\boldsymbol{U}_i) + \sum_{t=0}^{T-1} \boldsymbol{\lambda}_t^{\mathrm{imp}} \boldsymbol{U}_{i,t}^{\mathrm{imp}} - \sum_{t=0}^{T-1} \boldsymbol{\lambda}_t^{\mathrm{exp}} \boldsymbol{U}_{i,t}^{\mathrm{exp}} \bigg) .$$

Central System subproblem

$$\min_{\boldsymbol{U}} \mathbb{E}\bigg(J(\boldsymbol{U}) - \sum_{t=0}^{T-1} \boldsymbol{\lambda}_t^{\mathrm{imp}} \boldsymbol{U}_t^{\mathrm{imp}} + \sum_{t=0}^{T-1} \boldsymbol{\lambda}_t^{\mathrm{exp}} \boldsymbol{U}_t^{\mathrm{exp}} \bigg) .$$

- The multipliers $\boldsymbol{\lambda}_t^{\mathrm{imp}}$ play the role of energy import prices $\boldsymbol{P}_t$, that is, the price at which **CS** sells energy to the **DC**'s.
- The multipliers $\boldsymbol{\lambda}_t^{\mathrm{exp}}$ act as a correction of the price p^{oa}.

$\rightsquigarrow$ perfect competition (social optimum).

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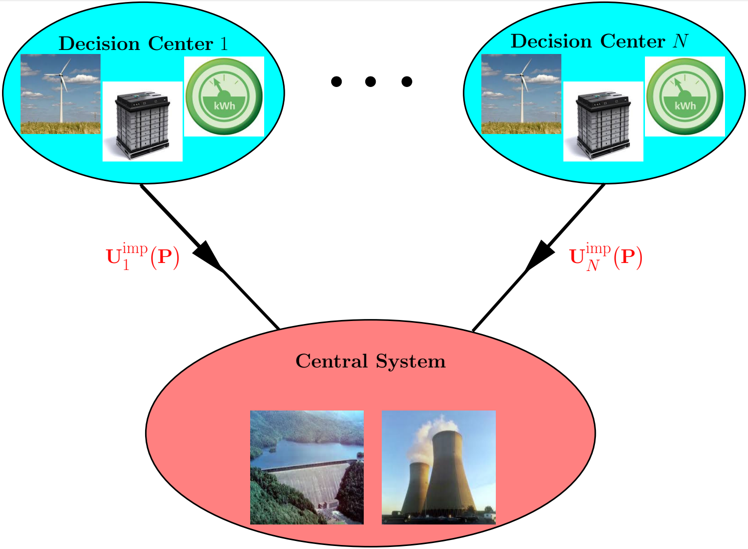
Another Management Point of View

The decision centers (followers) react in a optimal manner to price decisions taken by the central system. The central system (leader) anticipates the reactions of the decision centers to formulate and solve its own optimization problem.

- For a given price process $\boldsymbol{P}$, each decision center solves an optimization problem in which it may import energy from the central system at this price; the solutions $\widehat{\boldsymbol{U}}_i^{\mathrm{imp}}(\boldsymbol{P})$ are available for the central system.
- The central system incorporates the set of best responses $\widehat{\boldsymbol{U}}_i^{\mathrm{imp}}(\boldsymbol{P})$ of all decision centers in its optimization problem and maximize its revenue with respect to the prices $\boldsymbol{P}$.

Bilevel optimization problem in a dynamic and stochastic setting!

Leader-Follower Management



Leader-Follower Approach

In such a leader-follower approach, the central system solves the following optimization problem:

$$\min_{\boldsymbol{P}} \min_{\boldsymbol{U}} \mathbb{E}\left(J(\boldsymbol{U}) - \sum_{t=0}^{T-1} \boldsymbol{P}_t \left(\sum_{i=1}^{N_{\mathrm{dc}}} \widehat{\boldsymbol{U}}_{i,t}^{\mathrm{imp}}(\boldsymbol{P})\right)\right) ,$$

where $\widehat{\boldsymbol{U}}_i^{\mathrm{imp}}(\boldsymbol{P})$ is the best response of $\mathbf{DC}_i$:

$$\widehat{\boldsymbol{U}}_i^{\mathrm{imp}} : \boldsymbol{P} \longrightarrow \arg\min_{\boldsymbol{U}_i} \mathbb{E}\left(J_i(\boldsymbol{U}_i) + \sum_{t=0}^{T-1} \boldsymbol{P}_t \boldsymbol{U}_{i,t}^{\mathrm{imp}}\right) .$$

$\leadsto$ Stackelberg competition.

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Demand Response Management

Work based on the report by R. Carrasco [Carrasco et al, 2013].

The objective is to build a management mechanism for a system involving a utility company providing energy to N final consumers.

- The company has two tools to control the energy demand:
  - demand shifting,
  - demand shedding.

- The company procures energy thanks to a two-stage market:
  - day-ahead market (DA),
  - real-time market (RT).

The problem is formulated on a discrete time horizon $\{0, \dots, T\}$.

Demand Model

The demand of each final consumer i consists of three parts:

1. non-moveable demand $\boldsymbol{Q}_{i,t}^{(n)}$ (random variable),
2. sheddable demand $q_{i,t}^{(s)}$: consumer i may shed a portion $y_{i,t}$ of demand $q_{i,t}^{(s)}$, incurring a discomfort cost $D_i(y_{i,t})$,
3. dispatchable demand $\widehat{q}_i^{(d)}$ inside a time window $[\underline{t}_i, \overline{t}_i]$: the associated consumption $x_{i,t}$ at time t is such that

$$\sum_{t \in [\underline{t}_i, \overline{t}_i]} x_{i,t} = \widehat{q}_i^{(d)} .$$

The control variables for demand shaping are the $y_{i,t}$'s and $x_{i,t}$'s.

Demand Model II

- The sheddable and dispatchable demands are charged by the company at price B^f, and the non-moveable part at price B_t^v.
- To incite shedding, the company gives a compensation $p_t^{(s)}$ to consumer i at time t per unit of load shed.

The total cost function of consumer i is thus:[2]

$$J_i(y_i) = \sum_{t=0}^{T-1} \underbrace{B_t^v \cdot \boldsymbol{Q}_{i,t}^{(n)} + B^f \cdot \left(q_{i,t}^{(s)} - y_{i,t} + x_{i,t}\right)}_{\mathcal{B}_{i,t}(x_{i,t}, y_{i,t})} - p_t^{(s)} \cdot y_{i,t} + D_i(y_{i,t}) \; .$$

[2] Note that this cost does not depend on the $x_{i,t}$'s since $\sum_t x_{i,t} = \widehat{q}_i^{(d)}$.

Procurement Model

We assume that the energy prices p_t^{da} on the day-ahead market are known, whereas the prices $\boldsymbol{P}_t^{\mathrm{rt}}$ on the real-time market are random. The utility company chooses the energy amount $\widetilde{q}_t^{(n)}$ to buy on the day-ahead market in order to hedge the non-moveable demand and buy the remaining energy $\big(\boldsymbol{Q}_t^{(n)} - \widetilde{q}_t^{(n)}\big)^+$ on the real-time market.

The total revenue function of the utility company writes:

$$
\begin{aligned}
J(x, y, \widetilde{q}^{(n)}) = \sum_{t=0}^{T-1} \Bigg(\sum_{i=1}^{N} \Big(\mathcal{B}_{i,t}(x_{i,t}, y_{i,t}) - p_t^{(s)} \cdot y_{i,t} \Big) \\
- p_t^{\mathrm{da}} \cdot \Big(\sum_{i=1}^{N} \big(q_{i,t}^{(s)} - y_{i,t} + x_{i,t} \big) + \widetilde{q}_t^{(n)} \Big) \\
- \boldsymbol{P}_t^{\mathrm{rt}} \cdot \Big(\sum_{i=1}^{N} \boldsymbol{Q}_{i,t}^{(n)} - \widetilde{q}_t^{(n)} \Big)^+ \Bigg) .
\end{aligned}
$$

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Leader-Follower Approach

- Each final consumer (follower) reacts in a optimal manner to the compensation prices offered by the utility company for shedding (recall that the cost function of a consumer does not depend on the allocation $\{x_{i,t}\}$ of the dispatchable demand).
- The utility company (leader) anticipates the answers of the final consumers in order to set compensation prices that maximize its revenue.

Management Mechanism

- Knowing the compensation prices $p_t^{(s)}$, each final consumer determines its shedding strategy $\widehat{y}_i(p^{(s)})$ by minimizing the cost function $J_i(y_i)$. This minimization reduces to a bunch of problems indexed by (i, t):

$$\min_{y_{i,t}} \; -B^f \cdot y_{i,t} - p_t^{(s)} \cdot y_{i,t} + D_i(y_{i,t}) \; .$$

- The utility company incorporates these best responses and computes the prices $p_t^{(s)}$ in order to maximize its revenue:

$$\max_{p^{(s)}} \; \max_{x, \widetilde{q}^{(n)}} \; \mathbb{E}\Big(J\big(x, \widehat{y}(p^{(s)}), \widetilde{q}^{(n)}\big)\Big) \; .$$

Bilevel optimization problem: the best responses $\widehat{y}_i(p^{(s)})$ are easy to obtain once the discomfort functions D_i are known!

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Conclusions

Distributed production: major challenges to tackle the problem!

- The centralized management corresponds to a large-scale stochastic dynamic problem, non solvable using standard methods.
- In the leader-follower approach,
  - solving the optimization problem associated to a decision center for a given price process $\boldsymbol{P}$ is hard,
  - it is necessary to handle various constraints (measurability),
  - so that the classical ways to solve the bilevel optimization problem seem to be out of reach.

Demand response: the problem seems to be more tractable.

- How to compute the tariff structure (B^f, B^v)?

To be discussed this afternoon by the LASON team...

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Optimisation pour la gestion de la production d'électricité dans un contexte smart grid à l'aide de méthodes de décomposition coordination stochastique.
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Working paper, 2013.