DATAZERO: Powering a Data Center Disconnected from the Grid

Alexis Barreaux, Marwa Haddad, Jean-Marc Nicod, Marie-Cécile Péra, Christophe Varnier

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Data Centers and energy efficiency

Does using IT technologies have any consequences ?

- IT consumes a huge amount of energy : 56,5 TWh in France (2015)
  - Annual consumption of 8,282,000 French households
  - Expected increase of +25% in 2030
  - 2.5% of France's carbon footprint

Electricity consumption of French datacenters in 2015 reached approximately
10 TWh ≈ 17.6%
Data Centers reached 4 % of the global energy consumption in 2015
8 % in 2030 ?

increasing the energy efficiency of data-centers

supplying data-centers with only green energy

DATAZERO: an innovative data-center model

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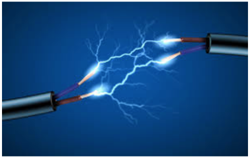


Adapting the IT load to
the available power
&
Adapting the power to
the incoming IT load

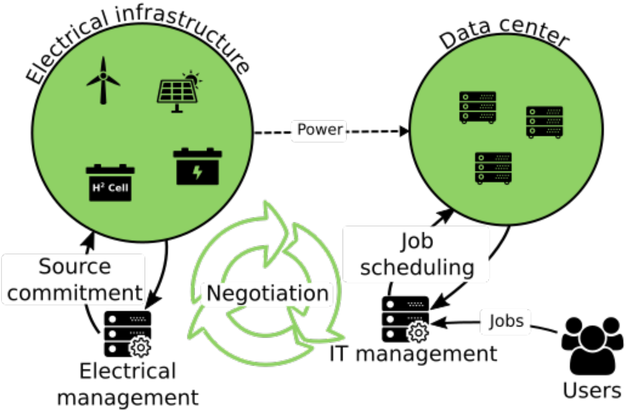
while using a mix of only green energy sources (without grid power usage)

DATAZERO: an innovative data-center model

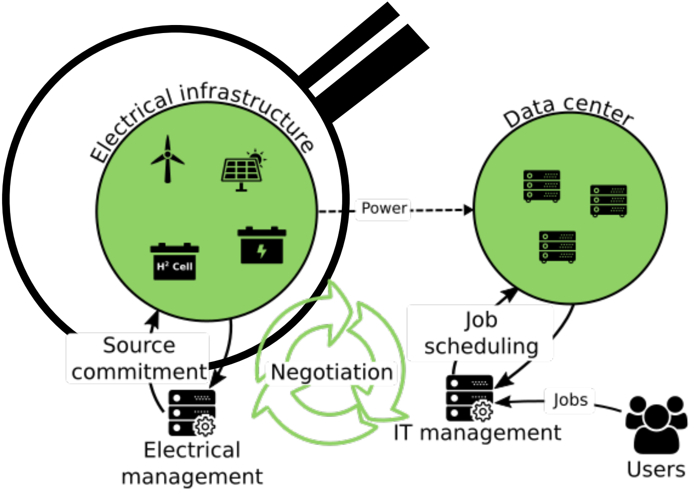
The question that we address in DATAZERO is:

⇒ How to **size** and **manage** a data center powered solely by renewable energy sources ?

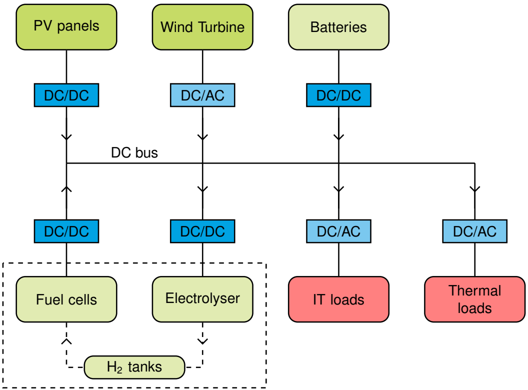
DATAZERO: the big picture



DATAZERO: the big picture

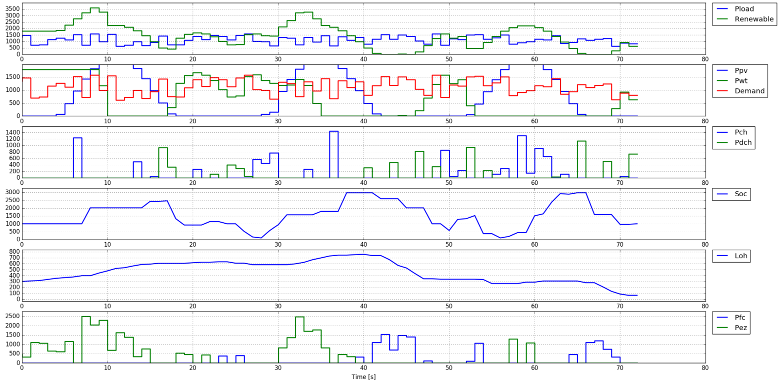


Power supply architecture



Electrical component usage over 72 hours, hour by hour

$\mathcal{H}$ = 72 hours (3 days)



Problem statement

The system is composed of different electrical sources:

- **Primary sources**: basic power to supply the data center (solar panels, wind turbines)
- **Secondary sources**: storage elements (batteries and fuel cell)

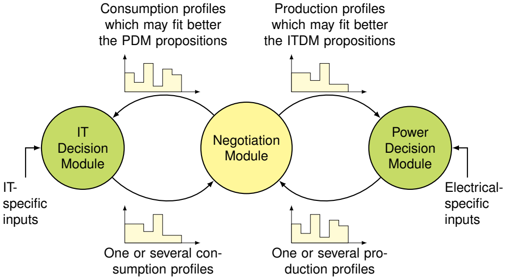
$\Rightarrow$ a decision has to be taken for each storage at any time $t \in \mathcal{H}$

- Horizon $\mathcal{H}$ discretized into K intervals Δt
- one decision is valid for any t s. t. $k\Delta t \leq t < (k+1)\Delta t$ with $k \in [\![0, K-1]\!]$

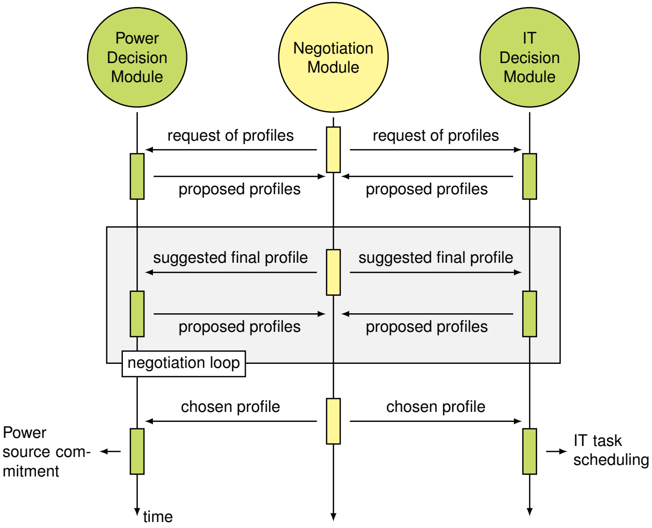
Optimization problem

Defining the best use of storage to meet the power demand

The negotiation loop



The negotiation loop

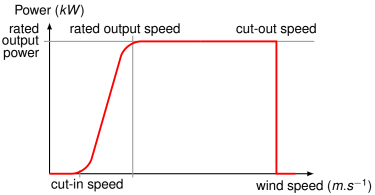


For each period k ($k \in [\![0, K-1]\!]$):

Wind Turbines

$$Pwt_k = Pw_k \times A_{wT} \times \eta_{wT}$$

$$Pw_k = \begin{cases} 0 & \text{if} \quad V_k \leq Vci \\ Pr \cdot \dfrac{V_k - Vci}{Vr - Vci} & \text{if} \quad Vci < V_k \leq Vr \\ Pr & \text{if} \quad Vr < V_k \leq Vco \\ 0 & \text{if} \quad Vco < V_k \end{cases}$$

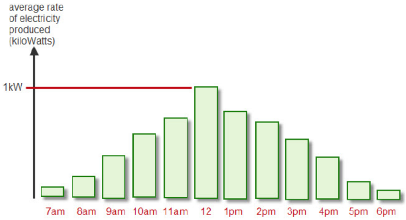


Model: solar panels

Solar Panels

$$Ppv_k = I_k \times Apv \times \eta_{pv}$$

with $k \in [\![0, K-1]\!]$



Model: the battery state of charge

For each time step $k \in [\![0, K]\!]$)

State of charge at time $k\Delta t$

$$SOC_k = SOC_{k-1} \times (1 - \sigma) + \frac{Pch_{k-1} \times \eta_{ch} \times \Delta t - \frac{Pdch_{k-1}}{\eta_{dch}} \times \Delta t}{Cbat}$$

$$\text{with} \quad SOCmin \leq SOC_k \leq SOCmax$$

- σ being the self-discharge rate
- Pch_{k-1}, $Pdch_{k-1}$ resp. the charging and discharging power
- η_{ch}, η_{dch} resp. the charging and discharging efficiency

Model: the battery state of charge

For each time step $k \in [\![0, K]\!])$

Mutual exclusion between charging and discharging processes

$$SOC_k = \min\{SOC_{k-1} \times (1-\sigma) + \frac{Pch_{k-1} \times \eta_{ch} \times \Delta t}{CBat}, SOCmax\} \text{ if } Pch_{k-1} > 0$$

$$SOC_k = \max\{SOC_{k-1} \times (1-\sigma) - \frac{Pdch_{k-1}}{\eta_{dch} CBat} \times \Delta t, SOCmin\} \text{ if } Pdch_{k-1} > 0$$

Model: Electrolysers

For each period k ($k \in [\![0, K-1]\!]$):

Operating power for the kth period

$$\frac{Pez_k \times \Delta t \times \eta_{ez}}{HHVh_2} \leq Qezmax$$

with $Pezmin \leq Pez_k \leq Pezmax$
or $Pez_k = 0$

- *Pezmin*, *Pezmax* being the operating range of the electrolyzer
- *Qezmax* the electrolyzer H_2 mass max flow (kg)
- η_{ez} the efficiency of the electrolyzer and $HHVh_2$ thex hydrogen higher heating value

Model: Fuel Cells

For each period k ($k \in [\![0, K-1]\!]$):

Output power for the kth period

$$\frac{Pfc_k \times \Delta t}{LHVh_2 \times \eta_{fc}} \leq Qfcmax$$

with $Pfcmin \leq Pfc_k \leq Pfcmax$
or $Pfc_k = 0$

- $Pfcmin$, $Pfcmax$ being the operating range of the fuel cell
- $Qfcmax$ being the maximum H_2 mass flow (kg) passing by the fuel cell
- η_{fc} the efficiency and $LHVh_2$ the low heating value of hydrogen

Model: H_2 tank

For each time step k ($k \in [\![0, K]\!]$):

Level of hydrogen at time $k\Delta t$

$$LOH_k = LOH_{k-1} + \frac{Pez_{k-1} \times \Delta t \times \eta_{ez}}{LHVh_2} - \frac{Pfc_{k-1} \times \Delta t}{LHVh_2 \times \eta_{fc}}$$

with $0 \leq LOH_k \leq LOHmax$

- LOH_0 is the initial value of the level of hydrogen
- η_{tank} the efficiency related to the hydrogen relaxation

Model: Flow conservation

For each period k ($k \in [\![0, K-1]\!]$):

Primary sources are used for:

- Hydrogen production (Pez_k)
- Charging the batteries (Pch_k)
- Satisfying the data center power demand ($Pload_k$)

Additional electrical power is delivered by the fuel cells (Pfc_k) and batteries ($Pdch_k$) if there is not enough renewable energy

To fullfill the demand, one has to satisfy

$$Pload_k \leq Pwt_k + Ppv_k + (Pfc_k + Pdch_k - Pez_k - Pch_k) \times \eta_{inv}$$

Additional constraints

- When a Fuel Cell is working, Batteries are not charging
- When Batteries are discharging, Electrolysers are not in use
- $$\begin{cases} SOC_K = SOC_0 = SOCinit & \text{if } K < 24 \\ SOC_k = SOC_0 = SOCinit & \text{if } K \geq 24 \\ \quad \text{and } k \equiv 0 \pmod{24} \; (k \in [\![0, K]\!]) \end{cases}$$

Linearization of the battery state of charge

Let x_k be a binary variable, Pch_k and $Pdch_k$ two rational variables s.t.

- $x_k = 1$ when the battery is charging
- $x_k = 0$ otherwise
- $\begin{cases} Pch_k & \leq x_k \times Pchmax \\ Pdch_k & = (1 - x_k) \times Pdchmax \end{cases}$

New equations for SOC_k

$$\begin{cases} SOCmin \leq SOC_k \leq SOCmax \\ SOC_k = SOC_{k-1}(1 - \sigma) + \dfrac{Pch_{k-1}\Delta t \times \eta_{ch} - Pdch_{k-1}\Delta t / \eta_{dch}}{CBat} \end{cases}$$

Linearization of constraints concerning electrolysers

Let y_k be a binary variable and Pez_k s.t.

- $y_k = 1$ when $Pezmin \leq Pez_k \leq Pezmax$
- $y_k = 0$ when $Pez_k = 0$

Linearization of Pez_k

$$Pez_k \geq y_k \times Pezmin$$
$$Pez_k \leq y_k \times Pezmax$$

Linearization of constraints concerning fuel cells

Let z_k be a binary variable and Pfc_k s.t.

- $z_k = 1$ when $Pfcmin \leq Pfc_k \leq Pfcmax$
- $z_k = 0$ when $Pfc_k = 0$

Linearization of Pfc_k

$$Pfc_k \geq z_k \times Pfcmin$$
$$Pfc_k \leq z_k \times Pfcmax$$

Mutual exclusion between electrolysers and fuel cells

$$1 - y_k - z_k \geq 0 \qquad \forall k$$

Mutual exclusion 1/2

Mutual exclusion between batteries and hydrogen system

1. The battery is in charge ($x_k = 1$) while electrolyzer can be in use ($y_k = 0$ or 1) and obviously fuel cell is stopped ($z_k = 0$).
2. The battery is discharging ($x_k = 0$) then fuel cell can be in use ($z_k = 0$ or 1) and the electrolyzer has to be stopped ($y_k = 0$)
3. Starting and stopping the fuel cell and electrolyzer is allowed in this problem

Mutual exclusion 2/2

Truth table

x_k	y_k	z_k
0	0	0
0	0	1
1	0	0
1	1	0

Mutual exclusion 2/2

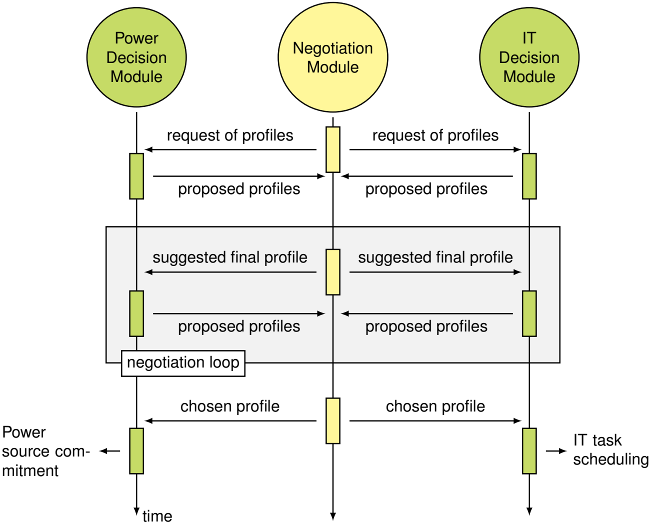
Truth table

x_k	y_k	z_k
0	0	0
0	0	1
1	0	0
1	1	0

Additional constraints

$$y_k \leq x_k$$
$$z_k \leq 1 - x_k$$

Objective functions



Objective function 1: Do the best you can without any constraint

Providing the maximum constant profile

$$\text{maximize} \quad Pprod$$

- $Pprod \leq Pwt_k + Ppv_k + (Pfc_k + Pdch_k - Pez_k - Pch_k)\eta_{inv}$
- $LOHtarget_D \leq LOH_K$

Providing the maximum non constant profile

$$\text{maximize} \quad \sum_k Pprod_k$$

- $Pprod_k \leq Pwt_k + Ppv_k + (Pfc_k + Pdch_k - Pez_k - Pch_k)\eta_{inv}$
- $LOHtarget_D \leq LOH_K$

Objective function 2: Be as close as possible to the demand

Principle (*Match profile base*)

- PDM attempts to match to a requested profile ($PLoad_k$) given by the negotiation module
- The gap in power production is associated with a relax factor α

Objective and additional constraints

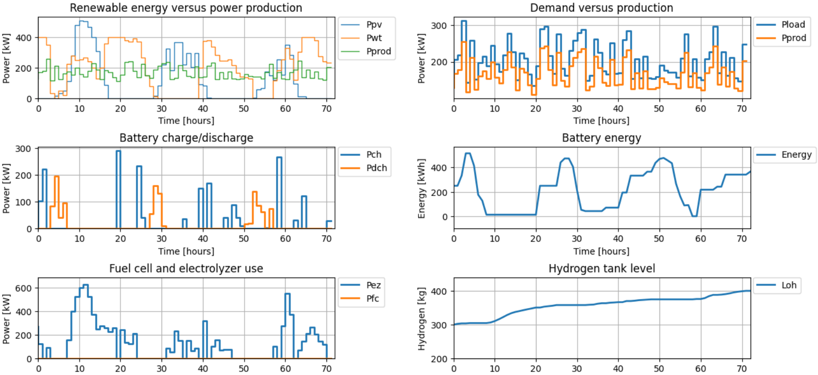
$$\min \alpha$$

$$s.c.$$

$$Pprod_k \geq (1 - \alpha) \times Pload_k \qquad \forall k \qquad (1)$$

$$LOH_K \geq LOHtarget_D \qquad (2)$$

Match profile production over a horizon of 72 hours



Objective function 2: improvement 1

Principle (*Match profile split*)

- α is split into K α_k $\forall k$
- to minimize $\max_k \alpha_k$, a new variable Z is introduced

Objective and additional constraints

$$\min Z$$
$$s.c. (1), (2)$$
$$Z \geq \alpha_k \qquad \forall k \qquad (3)$$

$\Rightarrow$ the solver doesn't try to minimize α_k once it has minimized its maximum, Z

Objective function 2: improvement 2

Principle (*Match profile updated*)

- A second term is introduced to force α_k to become smaller for all k
- a coefficient δ is introduced

Objective and additional constraints

$$\min Z + \delta \times \sum_{k \in K} \alpha_k$$

$$s.c.(1),(2),(3)$$

with $\delta \leq \frac{\varepsilon}{K}$ is sufficient to have $Z \leq Z^* + \varepsilon$ (Z^* the previous optimal)
$\Rightarrow$ in some tests have shown that all relax factors can remain equal

Objective function 2: improvement 3

Principle (*Match profile constricted mean*)

- we attempt to minimize the average of our relax factor by forcing them to stick around this mean
- coefficients ε_{up} and ε_{down} are introduced to allow more or less flexibility

Objective and additional constraints

$$\min \frac{1}{K} \times \sum_{k \in K} \alpha_k$$

$$s.c. (1), (2)$$

$$\alpha_k \leq \varepsilon_{up} + \frac{1}{K} \times \sum_{k \in K} \alpha_k \qquad \forall k \qquad (4)$$

$$\alpha_k \geq -\varepsilon_{down} + \frac{1}{K} \times \sum_{k \in K} \alpha_k \qquad \forall k \qquad (5)$$

Objective function 2: improvements 4 & 5

Principle

- Since we are mostly interested in improving our production, we can improve it through the introduction of a weighted mean

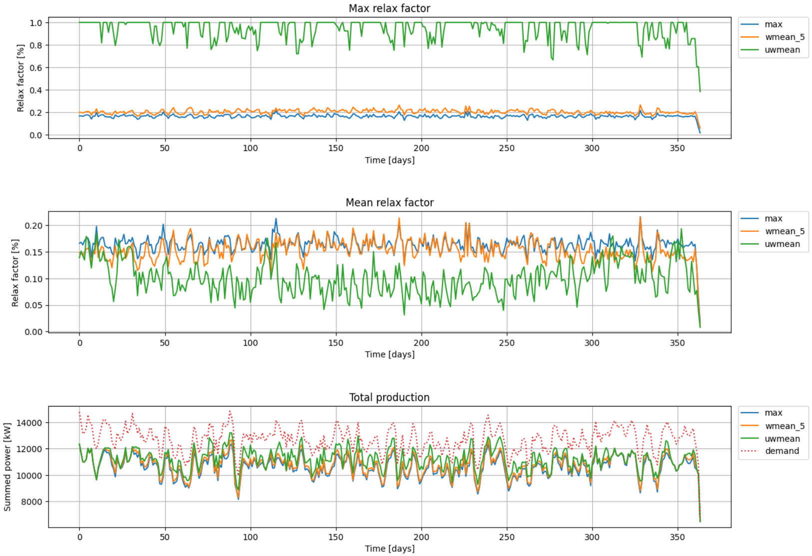
Match profile constricted weighted mean

$$\min \frac{1}{K} \times \sum_{k \in K} \alpha_k \times Pload_k$$
$$s.c.(1),(2),(4),(5)$$

Match profile unconstricted weighted mean

$$\min \frac{1}{K} \times \sum_{k \in K} \alpha_k \times Pload_k$$
$$s.c.(1),(2)$$

Experimental comparison



(**max**: for *Match profile updated*, **wmean_5**: for *Match profile constricted weighted mean* with $\varepsilon_{up} = \varepsilon_{down} = \frac{5}{100}$ and **uwmean** : for *Match profile unconstricted weighted mean*)

Conclusion

Summarize

- A model has been proposed for electrical components
- Integer linear programs have been written to respect the model and to address different optimization problems needed by the negotiation process (with less variables than before)
- A solution is found even if the number of variables is large

Perspectives

- Take uncertainty into account
- Take each component life cycle into account
- Take ageing of electrical components into account to address the whole optimization problems including maintenance operations for instance

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Stand-alone renewable power system scheduling for a green data center using integer linear programming

Maroua Haddad, Jean-Marc Nicod, Marie-Cécile Péra & Christophe Varnier

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