Energy management strategies for reducing a building's electricity costs after a PV installation

Student : *Pol Boudou, MA3 Energy Management & Sustainability*

Supervisors: Dr. *Jagdish Achara*
Prof. *Jean-Yves Le Boudec*

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Laboratory for Communications and Applications LCA

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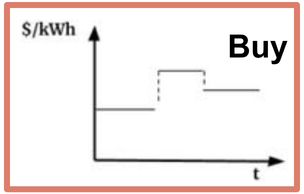
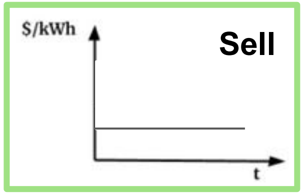
Baseline scenario

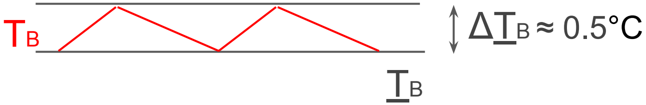


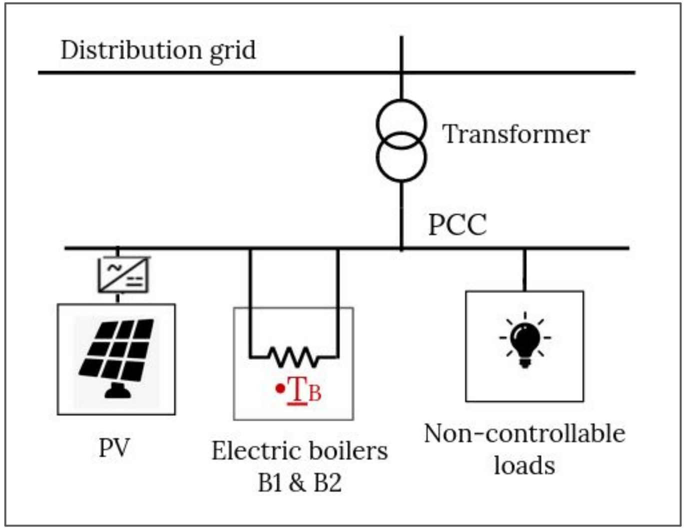


Assumptions:

- Variable buy price > sell price

- Two electric boilers, controlled by a thermostat fixing their temperature within $[\underline{T}_B \,;\, \underline{T}_B + \Delta T_B]$





EMS strategies

designed to reduce building’s electricity bill.

Strategy 1: Myopic control of boilers for self-consumption

<u>Rule-based logic</u> : maintain boilers between Temp bounds and supply PV surplus to boilers to the extent possible

at each timestep h:

Inputs (5): p_{PCC}, T_{B1}, p_{B1}, T_{B2}, p_{B2}

$p_x = p_{PCC}[h] - (p_{B1}[h] + p_{B2}[h])$
sort $\boldsymbol{T_B}[h]$ in ascending order

for each boiler k **do**

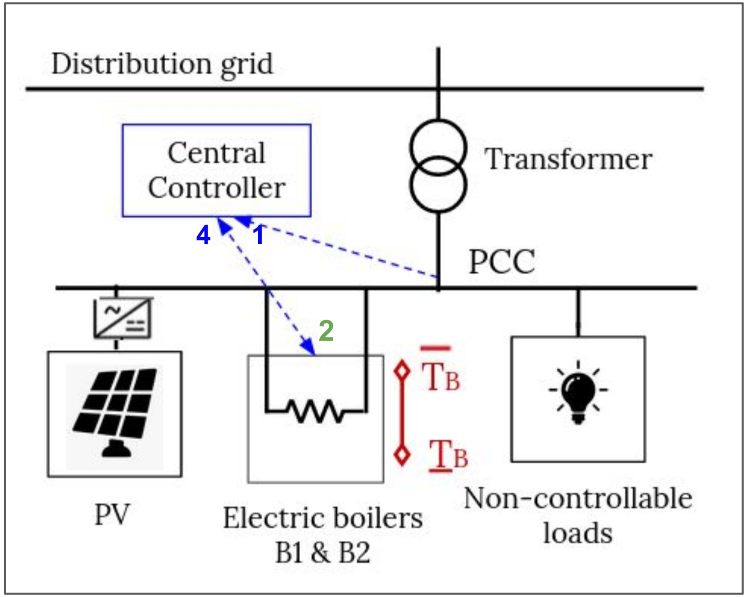
(set hysteresis state)
  set_$s_{B,k}[h]$ ($T_{B,k}[h]$, $s_{B,k}[h-1]$)

(max supply if boiler at critical state)
  if $s_{B,k}[h] = 1$ **then**
    $u_{B,k} \leftarrow \overline{P}_k$
    $p_x = p_x + u_{B,k}$

  else

(else supply using surplus)
    if $p_x > 0$ **then**
      $e_k^T[h] = max(0, \overline{T}_{B,k} - T_{B,k}[h])$
      $u_{B,k} \leftarrow max[-C_B \frac{e_k^T[h]}{\Delta t}, \overline{P}_k, -p_x]$
      $p_x = p_x + u_{B,k}$
    end
  end
end

Outputs (2): u_{B1}, u_{B2} (boiler commands)



<u>Limitations</u>: 1) myopic approach, 2) boiler model does not account for heat demand, 3) limited flexibility

Strategy 2: Myopic control of boilers & battery

Same rule-based control for boilers **+** battery backup:

→ Only charged when boilers at their max Temp or max Power

→ Discharged when negative surplus.

at each timestep h:

Inputs (7): p_{bat}, x_{bat}, p_{PCC}, T_{B1}, p_{B1}, T_{B2}, p_{B2}

$p_x = p_{PPC}[h] - (p_{B1}[h] + p_{B2}[h] + p_{bat}[h])$

take care of boilers as usual

if $p_x \geq 0$ **then**

$u_{bat} \leftarrow max[\frac{x_{bat}[h] - \overline{C}_{bat}}{\Delta t}, \overline{P}^{ch}_{bat}, -p_x]$ (charge battery)

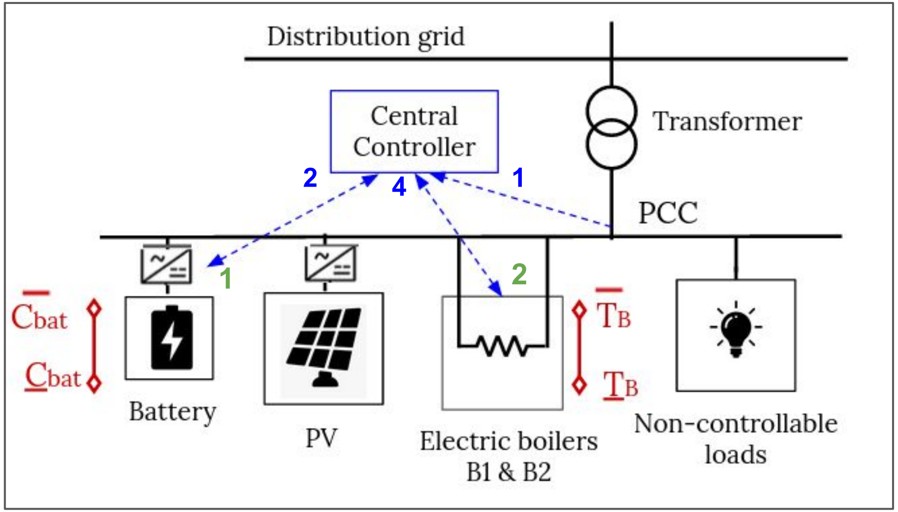
else

$u_{bat} \leftarrow min[\frac{x_{bat}[h] - \underline{C}_{bat}}{\Delta t}, \overline{P}^{disch}_{batat}, -p_x]$ (discharge battery)

end

return Control variables

Outputs (3): u_{bat}, u_{B1}, u_{B2} (battery & boiler commands)



Strategy 3: Model Predictive Control with boilers as controllable loads

At each time h, controller applies the first iteration of the solution of the following OP:

(Minimize cost)

$$min_{\boldsymbol{u_B},\boldsymbol{T_B},p_g} \sum_{h=t}^{t+H-1} C_{buy}[h]\ max(0,+p_g[h]) - C_{sell}[h]\ max(0,-p_g[h])$$

$s.t.$

(Power balance constraint)

$$p_g[h] + \hat{p}_x[h] + u_{B1}[h] + u_{B2}[h] = 0$$

for $k = 1,2:$

(Boiler models and power and temperature bounds)

$$T_{B,k}[h+1] = T_{B,k}[h] - A\ u_{B,k}[h] + B\ \frac{\hat{E}_{B,k}[h]}{T_{B,k}[h]} - C\ \hat{E}_{B,k}[h]$$

$$\overline{P}_{B,k} \leq u_{B,k}[h] \leq 0$$

$$\underline{T}_{B,k} \leq T_{B,k}[h] \leq \overline{T}_{B,k}$$

Strategy 4: Model Predictive Control with battery & boilers as controllable loads

At each time h, controller applies the first iteration of the solution of the following OP:

(Minimize cost)

$$min_{\boldsymbol{u_B},\boldsymbol{T_B},u_{bat},x_{bat}} \sum_{h=t}^{t+H-1} C_{buy}[h]\ max(0,+p_g[h]) - C_{sell}[h]\ max(0,-p_g[h])$$

s.t.

(Power balance constraint)

$$p_g[h] + \hat{p}_x[h] + u_{B1}[h] + u_{B2}[h] + u_{bat}[h] = 0$$

(Battery model and power and SoC bounds)

$$x_{bat}[h+1] = x_{bat}[h] + u_{bat}[h]\Delta t$$

$$\underline{C}_{bat} \leq x_{bat}[h] \leq \overline{C}_{bat}$$

$$\overline{P}_{bat}^{ch} \leq u_{bat}[h] \leq \overline{P}_{bat}^{disch}$$

for $k = 1, 2$:

(Boiler models and power and temperature bounds)

$$T_{B,k}[h+1] = T_{B,k}[h] - A\ u_{B,k}[h] + B\ \frac{\hat{E}_{B,k}[h]}{T_{B,k}[h]} - C\ \hat{E}_{B,k}[h]$$

$$\overline{P}_{B,k} \leq u_{B,k}[h] \leq 0$$

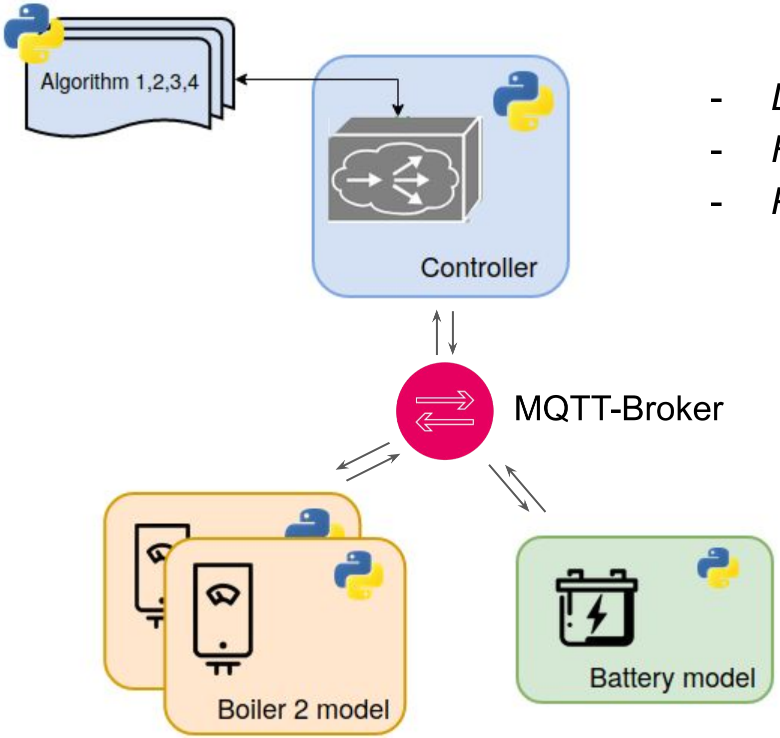
$$\underline{T}_{B,k} \leq T_{B,k}[h] \leq \overline{T}_{B,k}$$

<u>Limitations</u>: 1) need for forecasts (PV, loads, heat demand), 2) need for more computing time

Simulation framework

to allow us to compare all of the controller algorithms in the same building conditions.

Software implementation

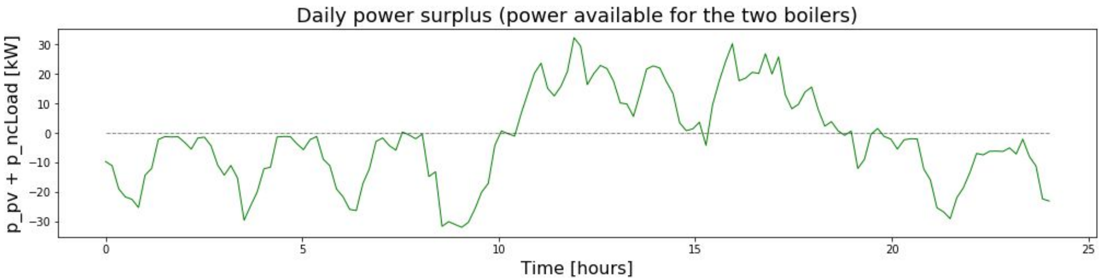


- *Listen* to units sensors
- *Run* algorithm
- *Publish* control commands

- *Simulate* entities state evolution
- *Publish* Power and Temp/Soc
- *Listen* to controller’s commands

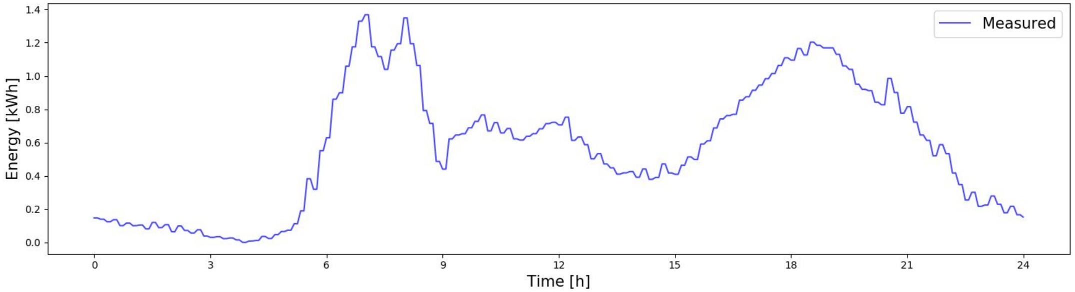
Building case

- Building’s power profile (without accounting for boilers)



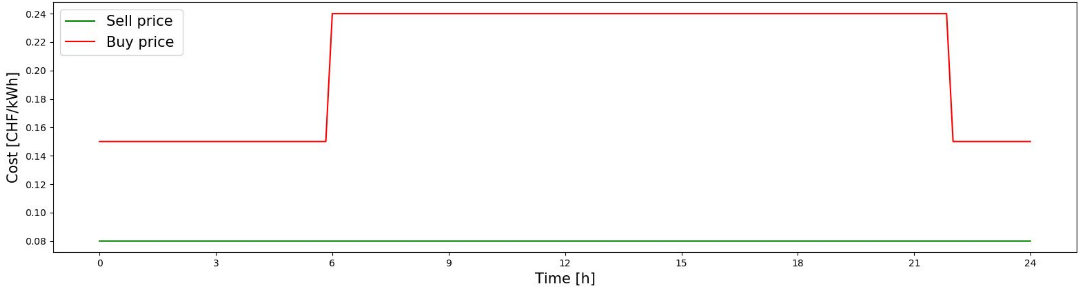
- two 800L boilers (P_{max} = -7.6 kW)
  - [40°C; 50°C]
  - [30°C; 60°C]

Boiler’s heat demand for water usage:



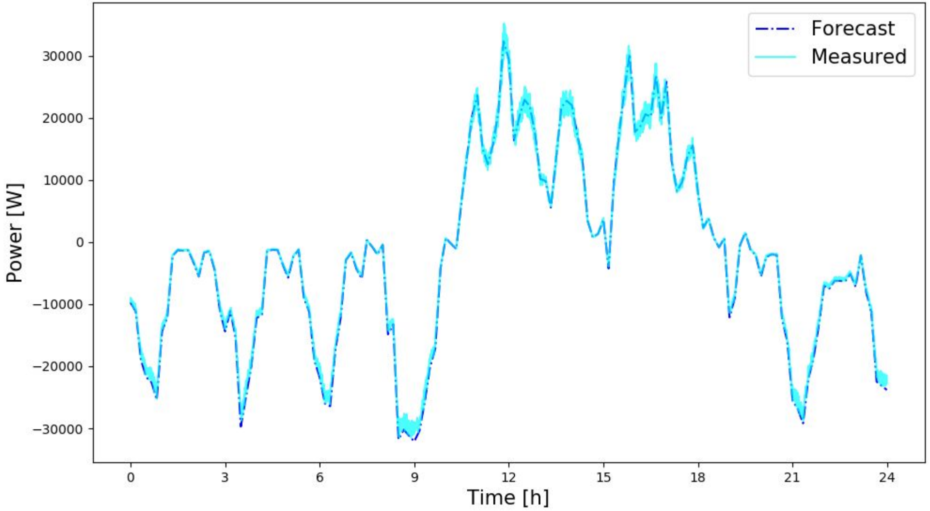
- 5 kWh battery ($P_{max/min} = \mp$ 5 kW)

- Time-of-Use tariff:

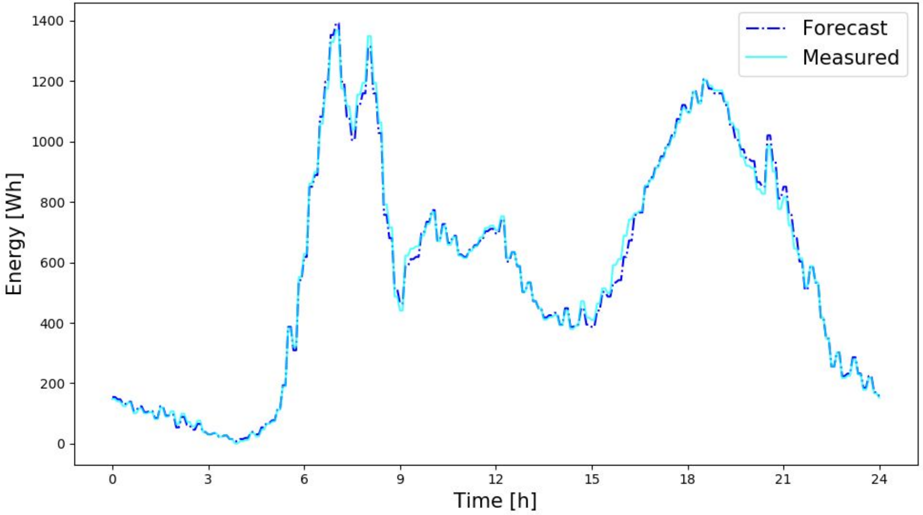


Forecasts and disturbances

Building power state



Building heat demand

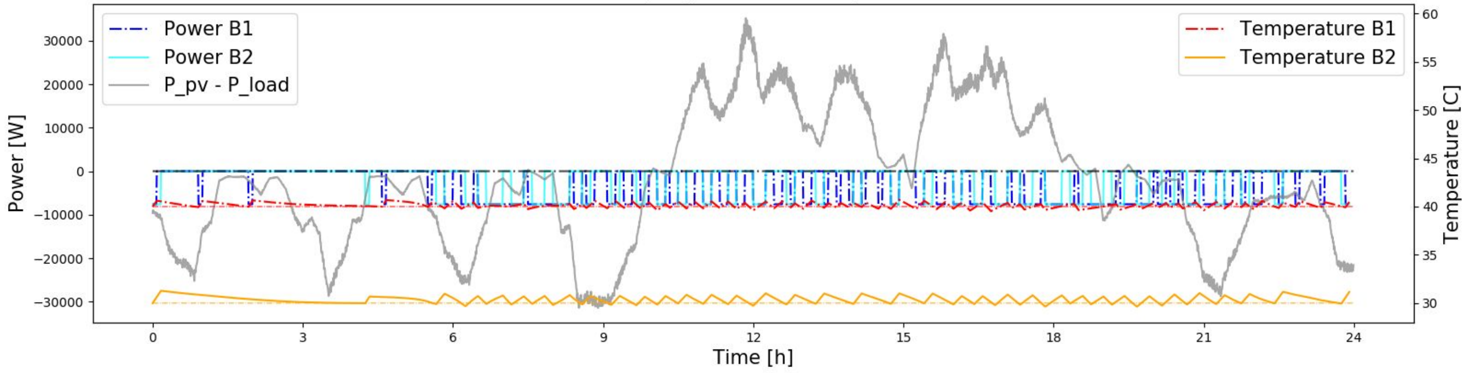


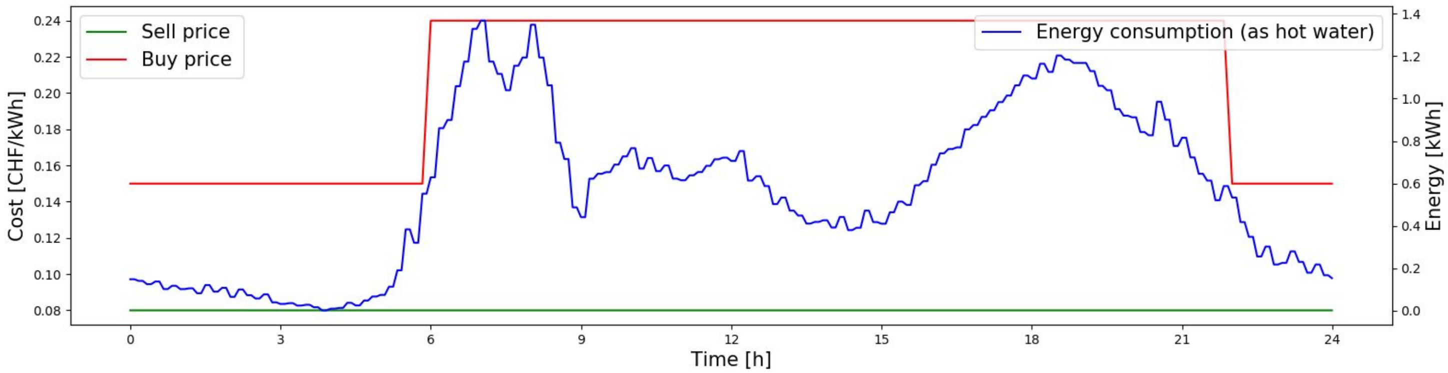
Results

Comparing behaviour and cost reduction of all four strategies

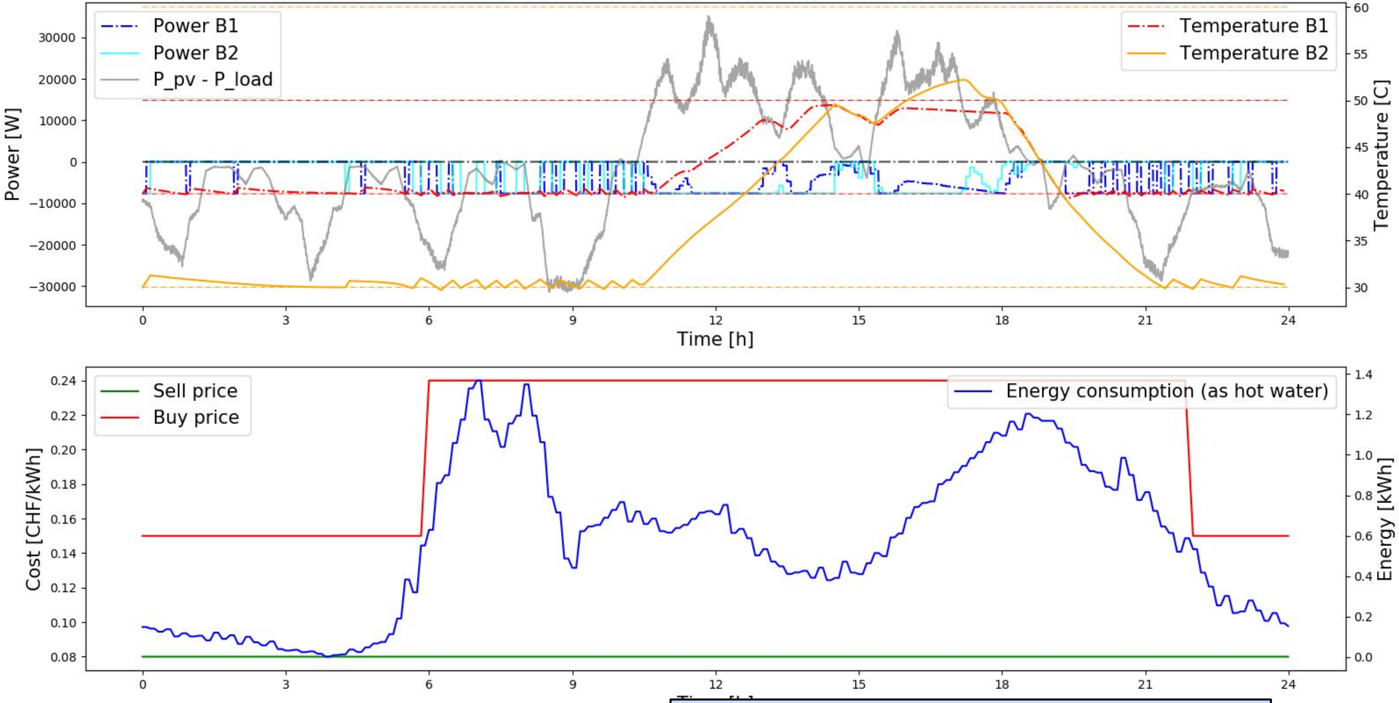
Baseline scenario

Daily cost: **47.91 CHF**





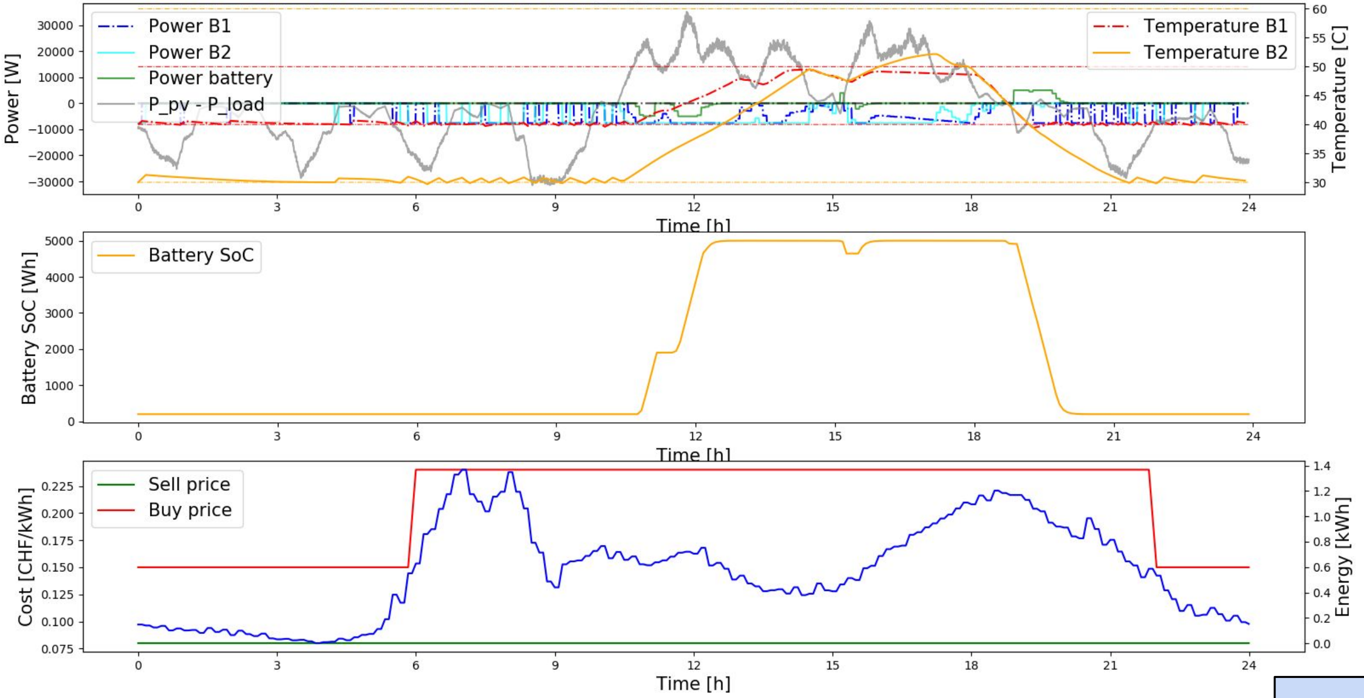
Strategy 1: myopic control boilers



Daily cost: 45.93 CHF

-4.13% reduction over Baseline

Strategy 2: myopic control of battery & boilers

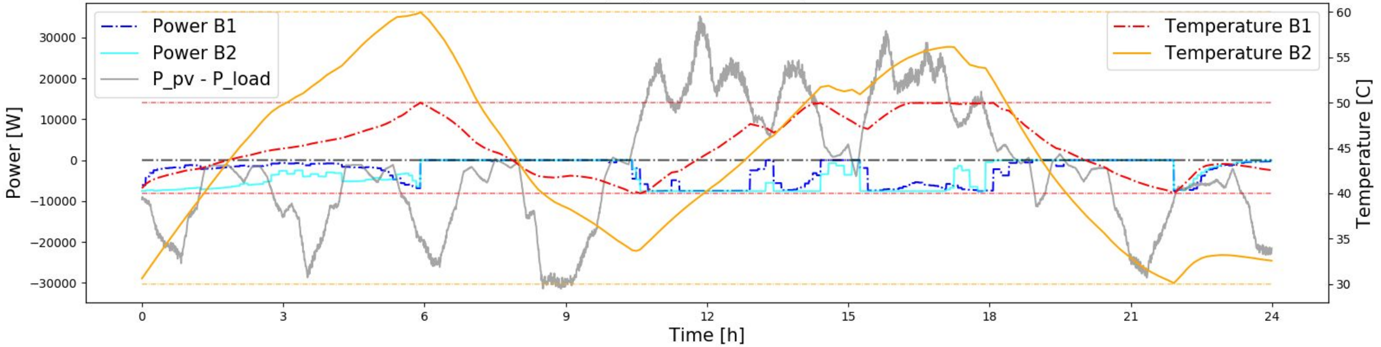


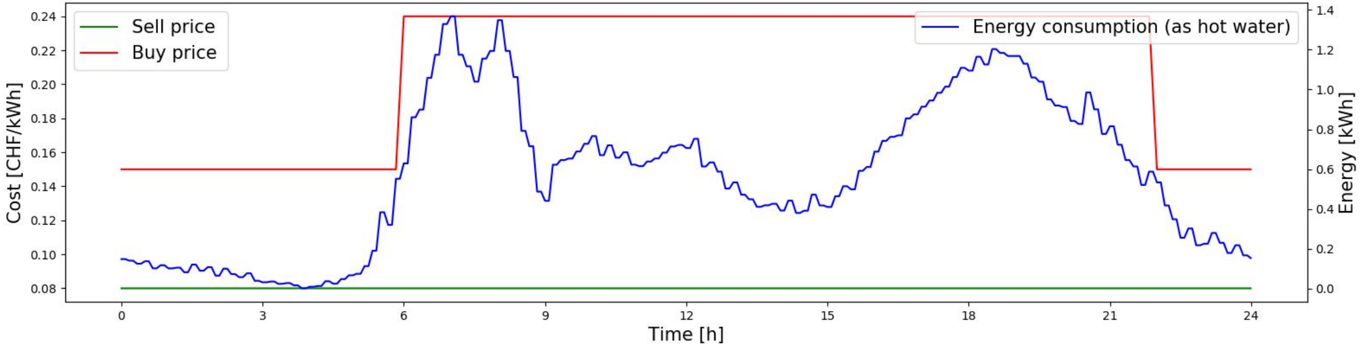
Daily cost: 45.22 CHF

-1.54% over strategy 1 **-5.61%** over Baseline

6 year battery payback time

Strategy 3: Applying MPC to boilers

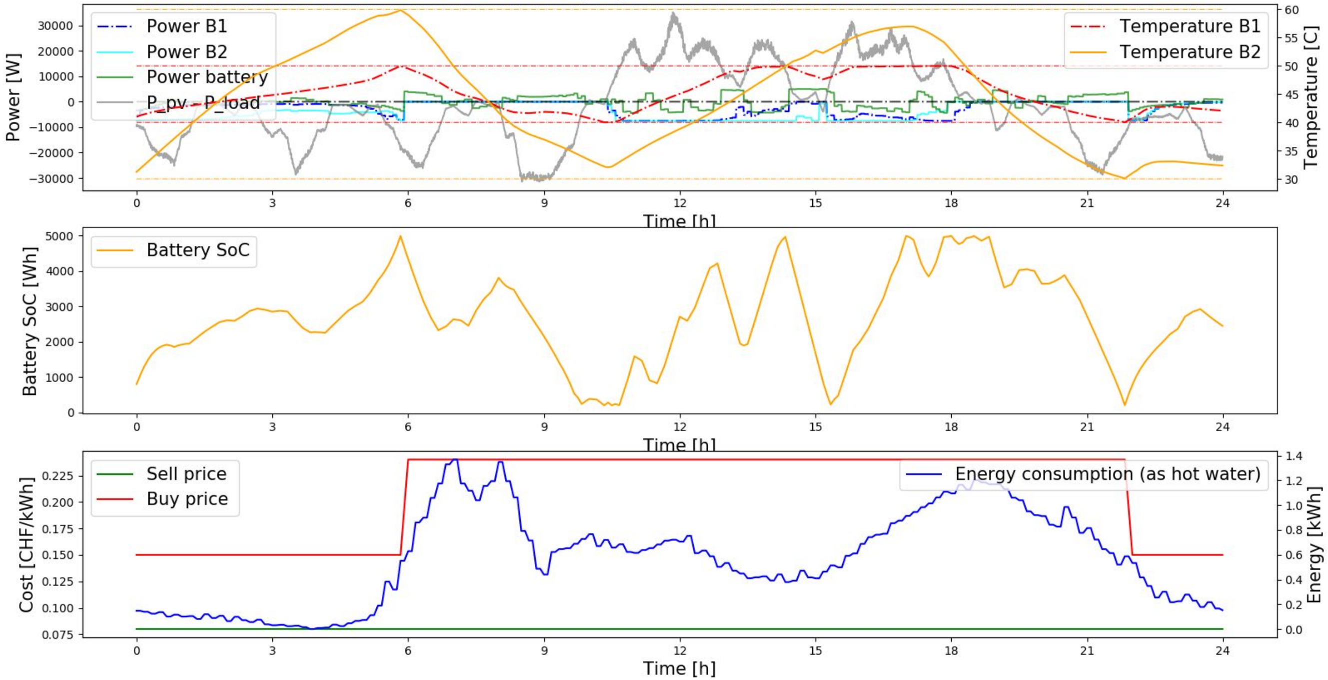




<u>Daily cost: 39.31 CHF</u>

-13.07% over strategy 2 **-18.0%** over Baseline

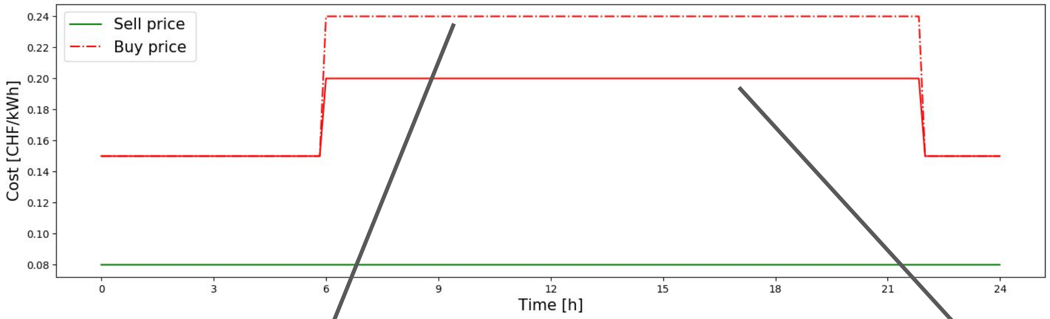
Strategy 4: applying MPC to battery & boilers



<u>Daily cost: 38.43 CHF</u>

-2.24% over strategy 3 **-19.79%** over Baseline

Reducing price variability



Baseline:
47.91 CHF

	Strategy 1 45.93 CHF	Strategy 2 45.22 CHF	Strategy 3 39.31 CHF	Strategy 4 38.43 CHF
Baseline	4.13%	5.61%	18.0%	19.79%
Strategy 1	×	1.54%	14.41%	16.33%
Strategy 2	×	×	13.07%	15.02%
Strategy 3	×	×	×	2.24%

MPC reduces costs by 14.41%
over a myopic control of boilers

Baseline:
41.11 CHF

	Strategy 1 40.02 CHF	Strategy 2 39.49 CHF	Strategy 3 35.55 CHF	Strategy 4 35.05 CHF
Baseline	2.65%	3.94%	13.52%	14.74%
Strategy 1	×	1.32%	11.17%	12.42%
Strategy 2	×	×	9.98%	11.24%
Strategy 3	×	×	×	1.41%

MPC reduces costs by 11.17%
over a myopic control of boilers

Conclusion

- **4.13%** estimated bill reduction with a primary EMS (communication + microcontroller + myopic algo).
- Battery can bring further savings to such EMS, after **6 years**
- As expected, MPC proves to be more effective (**18%** reduction).
    - MPC implementation computationally costly (100 s per iteration)
    - MPC satisfactory results boosted by:

        → High variability in the pricing structure.

        → High accuracy in forecasts

Appendix A

Boiler model

$$T_B[h+1] = T_B[h] - \frac{\Delta t}{C_B}\, u_B[h] - \frac{E[h]}{C_B} + \frac{E[h]\ T_{inc}}{C_B}\ \frac{1}{T_B[h]} \tag{5}$$

The boiler temperature state depends on 1) its present temperature ($T_B[h]$), 2) the temperature increase due to the supplied power ($\frac{\Delta t}{C_B}\ u_B[h]$), 3) the temperature decrease caused by the energy demanded by the building in terms of hot water ($\frac{E[h]}{C_B}$) and 4) the temperature decrease due to the incoming cold water, whose volume will depend on the energy drained but also on boiler's temperature ($\frac{E[h]\ T_{inc}}{C_B}\ \frac{1}{T_B[h]}$).

Appendix B

Linearizing MPC formulation

$$
\begin{aligned}
& min_{\boldsymbol{u_B}, \boldsymbol{T_B}, p_g} \sum_{h=t}^{t+H-1} C_{buy}[h]\ p_g^+[h] - C_{sell}[h]\ p_g^-[h] \\
& s.t. \\
& \quad p_g[h] + \hat{p}_x[h] + u_{B1}[h] + u_{B2}[h] = 0 \\
& \quad p_g^-[h] = max(0, -p_g[h]) \\
& \quad p_g^+[h] = max(0, +p_g[h]) \\
& \text{for } k = 1, 2 : \\
& \quad T_{B,k}[h+1] = T_{B,k}[h] - A\ u_{B,k}[h] + B\ \frac{\hat{E}_{B,k}[h]}{\underline{T_{B,k}[h]}} - C\ \hat{E}_{B,k}[h] \\
& \quad \overline{P}_{B,k} \leq u_{B,k}[h] \leq 0 \\
& \quad \underline{T}_{B,k} \leq T_{B,k}[h] \leq \overline{T}_{B,k}
\end{aligned}
$$

Nonlinear version

$$
\begin{aligned}
& T_{B,k}[h+1] = T_{B,k}[h] - A\ u_{B,k}[h] + B\ \hat{E}_{B,k}[h]\ \underline{\epsilon_{B,k}} - C\ \hat{E}_{B,k}[h] \\
& \epsilon_{B,k} = max(tan_i(\frac{1}{T_{B,k}[h]})\ \textbf{for}\ i \in [\underline{T}_{B,k}; \overline{T}_{B,k}])
\end{aligned}
$$

$$
\begin{aligned}
& min_{\boldsymbol{u_B}, \boldsymbol{T_B}, p_g, \phi, \boldsymbol{\epsilon_B}} \sum_{h=t}^{t+H-1} \phi + \underline{w\ (\epsilon_{B1} + \epsilon_{B2})} \\
& s.t. \\
& \quad p_g[h] + \hat{p}_x[h] + u_{B1}[h] + u_{B2}[h] = 0 \\
& \quad \phi \geq C_{buy}[h]\ p_g[h] \\
& \quad \phi \geq C_{sell}[h]\ p_g[h] \\
& \text{for } k = 1, 2 \\
& \quad T_{B,k}[h+1] = T_{B,k}[h] - A\ u_{B,k}[h] + B\ \hat{E}_{B,k}[h]\ \underline{\epsilon_{B,k}} - C\ \hat{E}_{B,k}[h] \\
& \quad \underline{\epsilon_{B,k}} \geq tan_i(\frac{1}{T_{B,k}[h]}) \quad \textbf{for}\ i \in [\underline{T}_{B,k}; \overline{T}_{B,k}] \\
& \quad \overline{P}_{B,k} \leq u_{B,k}[h] \leq 0 \\
& \quad \underline{T}_{B,k}[h+1] \leq T_{B,k}[h] \leq \overline{T}_{B,k}[h+1]
\end{aligned}
$$

Linear version

Strategy 1: Myopic control of boilers

<u>Rule-based logic</u> : at each timestep, maintain boilers between temp bounds and supply PV power surplus to boilers to the extent possible

Inputs: Power PCC, B1, B2 power & temp

For each boiler

Setting hysteresis state $s_{B,k}[h]$

Supplying if boiler at critical state

Supplying using surplus power

Outputs: B1,B2 actions

<u>Inputs:</u> $\boldsymbol{T_B}[h], p_{PCC}[h], p_{B1}[h], p_{B2}[h], \boldsymbol{s_B}[h-1]$
<u>Control variables:</u> $\boldsymbol{u_B}$
Initialize: for all k: **if**$(T_{B,k}[0] < T_{\Delta,k})$**:** $s_{B,k}[0] = 1$, **else:** $s_{B,k}[0] = 0$
Start
$\boldsymbol{u_B} \leftarrow 0$
$p_x = p_{PCC}[h] - (p_{B1}[h] + p_{B2}[h])$
sort $\boldsymbol{T_B}[h]$ in ascending order
for each boiler k **do**
  if $T_{B,k}[h] \geq \underline{T}_{B,k} + T_{\Delta,k}$ **then**
    $s_{B,k}[h] = 0$
  end
  if $T_{B,k}[h] \leq \underline{T}_{B,k}$ **then**
    $s_{B,k}[h] = 1$
  else
    $s_{B,k}[h] = s_{B,k}[h-1]$
  end
  if $s_{B,k}[h] = 1$ **then**
    $u_{B,k} \leftarrow \overline{P}_k$
    $p_x = p_x + u_{B,k}$
  else
    if $p_x > 0$ **then**
      $e_k^T[h] = max(0, \overline{T}_{B,k} - T_{B,k}[h])$
      $u_{B,k} \leftarrow max[-C_B \frac{e_k^T[h]}{\Delta t}, \overline{P}_k, -p_x]$
      $p_x = p_x + u_{B,k}$
    end
  end
end
return Control variables