

Design of an Energy Management System for buildings: a bottom up approach

Pol Boudou Perez

October 2019

1 Introduction

2 Problem statement

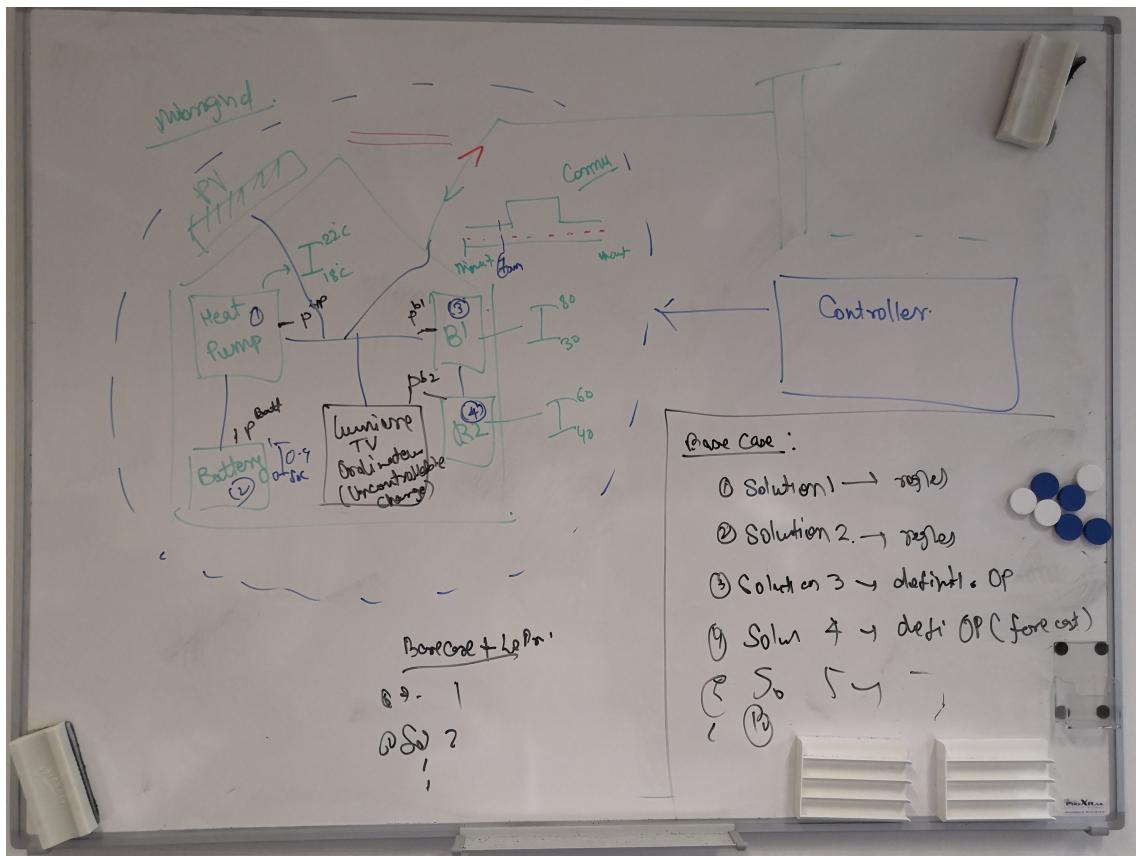


Figure 1: Microgrid sketch (to be changed)

A bottom up approach is taken. A baseline scenario is first proposed and its limitations are studied. Progressively, those limitations are tackled by adding features and complexity to the system, with the unique goal of reducing energy costs. Each of the added features are discussed and their downside are pointed.

3 Scenario 1

The first scenario describes the baseline case of a generic household. In order to produce locally and reduce its electricity bill, a PV system has been incorporated to the building. Now that it can also generate power and not only consume it as a load, the building can be seen as a grid-connected microgrid. In fact, the building can inject excess PV power into the grid via a single two-ways connection. Just as before the PV installation, the household can also consume from the grid whenever PV power is not enough to supply its different loads.

However, grid's electricity comes at a higher price. The feed-in tariff that the household gets for injecting power back to the grid is considerably lower than the cost of consuming electricity from such an unrestricted and reliable source. It is therefore the purpose of an Energy Management System (EMS) to maximise the self-consumption of PV power.

For that, the EMS has the ability to exploit the flexibility of the building. For instance, two electric boilers (B1 and B2) bring thermal storage capabilities to the household. An intelligent EMS would allow to operate those thermo-electric units under certain coordination to actively respond to the microgrid power fluctuations.

In this first scenario, the EMS objective is simply to take advantage of the flexibility of the two boilers. To ensure a certain hot-water supply, B1 and B2 should ideally be operated within min/max limits. Those two temperature ranges are the only degree of freedom for the EMS to operate. In contrast to the supply side which is non-controllable, the demand side can be controlled with the goal of matching PV production.

In a different category than boilers, the remaining household loads are non-controllable and represent another source of uncertainty. Those include lights, TV, washing machine and all human-switched appliances in general.

3.1 EMS Components and models

Regarding the EMS implementation, several features are needed. The physical quantities such as boiler temperatures and power consumed by the loads (boilers and non-controllable) need to be communicated to the controller, and same goes for PV generated power. It is assumed that the different loads are self-conscious about their state. For instance, boilers are equipped with temperature sensors. A power sensor is also able to measure the household power consumption (ignoring boilers, that have their own power sensors). Finally, the PV converter is aware of its power. All in all, in the first scenario, the EMS needs 4 measurement inputs.

A communication layer is in charge of broadcasting sensors data to the centralized controller. This one processes such inputs and computes an adequate control action for each of the controllable units. The output is communicated back to the loads, where the actuator ensures that the controller orders are executed.

In order to actively control boilers 1 and 2, a model of such thermal loads has to be incorporated. To avoid over complicating Scenario 1 and letting it as wide as possible, a very simplistic, linearly approximated model

is used. The water's thermal capacity C_w describes its ability (and the boiler's) to accumulate heat. Ignoring factors such as heat loss, hot-water consumption and electrical system efficiency, the temperature evolution in the boiler is given by the difference Equation 1.

$$p_b^{elec} = C_w \frac{dT_w}{\Delta t} \quad (1)$$

It is important to precise that the microgrid automatically balances power supply and demand. Under such assumption, any PV power not consumed by the building is absorbed by the grid without the necessity of any control action on the part of the EMS. Similarly, any power demand from loads that cannot be supplied by the PV system is supplied by the grid.

3.2 Notations

Control variables are named u , whereas measurement variables are named p for load's power or x for load's state. Capital letters designate constant parameters. Indexes refer to specific energy systems. Time value of the variables is be noted with $[h]$, where h designates the current discrete time period of length Δt , and goes from 0 to H . Regarding sign convention, a positive power refers to power that is injected into the microgrid, for instance by the PV system. A negative power is one that is absorbed by loads. Finally, underline ($\underline{\bullet}$) and overline ($\overline{\bullet}$) designate minimum and maximum values respectively and are subjected to the same sign convention.

PV system

p_{PV} : PV power (kW) (≥ 0)

Non-controllable loads

p_{nc} : power demanded by non-controllable loads (kW) (≤ 0)

Electric boilers

$u_{B,k}$: target power of boiler k (kW) (≤ 0)

$p_{B,k}$: actual power of boiler k (kW) (≤ 0)

$\overline{P}_{B,k}$: Max. power of boiler k (kW) (≤ 0)

$[\underline{T}_{B,k}; \overline{T}_{B,k}]$: lower and uppers limits on boiler's k hot-water temperature.

$T_{B,k}$: actual temperature of boiler k (°C)

Vectors $\hat{\mathbf{T}}_B[h]$ and $\hat{\mathbf{u}}_B$ regroup information of both boilers.

3.3 Control algorithm

The controller is configured by establishing rules determined by all possible system operating scenarios.

First, if the state of boilers is under or at the minimum limits $\underline{T}_{B,k}$, those are immediately supplied with their allowed maximum power $\overline{P}_{B,k}$.

Then, PV generation is taking into account and managed according a simple priority ladder. PV power is first used to feed non-controllable loads p_{nc} . If PV power is enough to supply the building's non-controllable loads, the variable $p_x = p_{PV} + p_{nc}$ refers to the excess free power in the microgrid available to feed flexible loads. Those come second in the PV priority ladder, and the boiler with the lower normalized temperature will be prioritized over the other. Assuming that the controller knows the different temperature limits, it is able to normalize the measured temperature according to those values and compare both boiler states.

When there is no excess power, the supply of non-controllable loads is insured by the grid.

Boilers temperature increase is defined in Equation 1 as a function of power input. By knowing the target temperature $\bar{T}_{B,k}$ and the measured temperature $T_{B,k}[h]$, the controller computes the error $e_k[h] = \bar{T}_{B,k} - T_{B,k}[h]$. With the boilers model, this error can be translated to a power, which is the power input needed to attain target temperature.

3.3.1 Pseudocode

Algorithm 1: Scenario 1: control of boilers

Executed every time-step h
Inputs: $\hat{T}_B[h], p_{PV}[h], p_{nc}[h]$
Control variables: \hat{u}_B

```

Start
 $\hat{u}_B \leftarrow 0$ 
 $p_x = p_{PV}[h] + p_{nc}[h]$ 
sort  $\hat{T}_B[h]$  in ascending order
for each boiler  $k$  do
    if  $T_{B,k} \leq \bar{T}_{B,k}$  then
         $u_{B,k} \leftarrow \bar{P}_k$ 
         $p_x = p_x + u_{B,k}$ 
    else
         $e_k[h] = \max(0, \bar{T}_{B,k} - T_{B,k}[h])$ 
         $u_{B,k} \leftarrow \max[-C_w \frac{e_k[h]}{\Delta t}, \bar{P}_k, \min(-p_x, 0)]$ 
         $p_x = p_x + u_{B,k}$ 
    end
end
return Control variables
End

```

3.4 Limitations

Being the baseline scenario, the described system presents several limitations. They are summarized in the following points and are related to energy management efficiency, system modelling and controller design/algoritm:

- Inter-interval power variations are not accounted by the controller.

- Very basic modelling of boiler functioning.
- ON/OFF control of boilers' power at lower temperature limit may overstimulate controller's action.
- Excess power might be re-injected into the grid for a lower price if boiler upper limits (both in terms of power and temperature) are attained.

First, the controller acts on the measures obtained at time h . It receives those measures and computes the best possible action for time h power state, which may not remain the same during the next Δt (until time $h + 1$). In the microgrid, power demand can be perfectly matching supply at the begining of each control action, but this matching ends once non-controllable power supply or demand varies. For instance, if excess is positive, it is supplied to boilers. A few milliseconds later, excess could decrease, forcing the main grid supply some of the power requested by boilers actuators. This would translate into unnecessary costs.

Forecasting is a potential solution to tackle the mismatch between microgrid's supply and demand between control time periods. For PV and non-controllable loads power, a short term forecasting agent would allow to estimate the inter-interval power variations and enable the controller to take actions based on those estimations.

A second limitation which has already been pointed makes reference to the use of a simplistic boiler model. Basically, the model does not account for hot-water consumption, which is a crucial point when its temperature wants to be controlled. Also, outside tank temperature as well as inlet temperature are not considered, and heat losses can therefore not be accounted. Having an incomplete model might give the controller a poor information, and power could be saved by incorporating a model that better describes reality. Eventually, such improved model would allow to use hot water consumption forecasts to further optimize control action.

A third limitation regarding the specific control algorithm has been identified. When handling a boiler at its lower temperature bounds, the controller only reacts when that particular temperature is reached. Because the condition only applies to that unique temperature $\underline{T}_{B,k}$, action stops right after temperature increases even if such increase is meaningless. This behaviour can create a constant action over the boiler, which might overstimulate the EMS and impede a smooth operation.

Finally, capacity limitations might force some of the locally produced power to be re-injected into the grid. If boilers' heat storage capacity is not big enough to absorb all PV power, power re-injected at lower price presents an economic disadvantage if the microgrid is latter in need of that extra power.

4 Scenario 2

In order to improve controllers action around boilers lower bound temperatures, an hysteresis behaviour can be added to controller's logic. Once this limit is reached, a binary variable $s_{B,k}$ is set to 1, which means that the boiler will be supplied until a new temperature target $T_{\Delta,k}$ above $\underline{T}_{B,k}$ is reached. As long as $s_{B,k}$ remains 1, boiler k will be supplied. Once the target temperature $T_{\Delta,k}$ is reached, $s_{B,k}$ will be set equal to 0, meaning that the lower limit temperature constraint has been successfully handled. Boiler will then be exclusively supplied by excess power until its lower bound is reached once again. For handling both boilers, the vector \hat{s}_B is defined.

Algorithm 2 presents how the hysteresis process would be implemented in Scenario 2.

Algorithm 2: Scenario 2: control of boilers with hysteresis over lower temperature limits

Executed every time-step h

Inputs: $\hat{T}_B[h]$, $p_{PV}[h]$, $p_{nc}[h]$, $\hat{s}_B[h - 1]$

Control variables: \hat{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

$\hat{u}_B \leftarrow 0$

$p_x = p_{PV}[h] + p_{nc}[h]$

sort $\hat{T}_B[h]$ in ascending order

for each boiler k **do**

if $T_{B,k}[h] \geq T_{\Delta,k}$ **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**

$| u_{B,k} \leftarrow \bar{P}_k$

$| p_x = p_x + u_{B,k}$

else

$| e_k[h] = \max(0, \bar{T}_{B,k} - T_{B,k}[h])$

$| u_{B,k} \leftarrow \max[-C_w \frac{e_k[h]}{\Delta t}, \bar{P}_k, \min(-p_x, 0)]$

$| p_x = p_x + u_{B,k}$

end

end

return Control variables

End

4.1 Limitations

One of the limitations of Scenario 1 has been tackled by the implementation of an hysteresis process for boiler control. Whenever a boiler's lower limit is attained, control logic supplies such boiler until a decent

temperature increase is reached. After that, both boiler and controller can forget about that lower limit, thus avoiding unnecessary power fluctuations inside the microgrid.

However, several other limitations presented in Scenario 1 are still present:

- Excess power might be re-injected into the grid for a lower price if boiler upper limits (both in terms of power and temperature) are attained.
- Inter-interval power variations are not accounted by the controller.
- Very basic modelling of boiler's temperature evolution.

5 Scenario 3

Scenario 1 and 2 proposed the base layer to profit from the building's PV installation. By adapting demand to supply, self-consumption could be maximised and therefore power demanded to the grid was reduced. However, at moments when boilers are fully powered or at maximum temperature, some excess power may be re-injected into the grid at a lower price.

A first solution to further maximise self-consumption inconvenience is to install into the building an energy storage battery system. This will add a level of flexibility to the microgrid/building and will be able to shape the power system fluctuations by both consuming and producing power.

Because the battery is only going to step in after the flexible loads have offered their flexibility, a small battery is the most cost-effective solution. In fact, it is not needed to store all PV power, but rather to give to the microgrid that little extra self-consumption ability. Moreover, putting the battery last in the power supply priority is going to reduce pointless charge/discharge cycles, which are the main source of aging/deterioration.

5.1 EMS Components and models

On top of the EMS architecture required for Scenario 1, the incorporation of the battery adds some complexity to the microgrid. A new control variable needs to be taken into account, and a battery model is needed for the controller to determine the adequate control action.

$$x_b[h+1] = x_b[h] - p_b[h] \Delta t \quad (2)$$

$$\underline{C}_b \leq x_b[h] \leq \bar{C}_b \quad (3)$$

$$\bar{P}_b^{ch} \leq p_b[h] \leq \bar{P}_b^{disch} \quad (4)$$

$$(5)$$

New variables and parameters need to be addressed by the EMS. The battery's State-of-Charge (SoC) x_b (kWh) and power p_b (kW) are measured and broadcasted to the controller. The controller communicates back the target power u_b (kW) to be supplied or demanded to the storage system. The simple battery model presented in Equation 2 allows the controller to set the correct battery power u_b to bring the battery to its targeted SoC. Constant parameters are again assumed to be known by the controller. \bar{C}_b and \underline{C}_b are respectively the maximum and minimum battery capacity (kWh). Regarding power limits, \bar{P}_b^{ch} (≤ 0) and \bar{P}_b^{disch} (≥ 0) are respectively the maximum charging and maximum discharging battery power (kW).

It is assumed that the battery software is ideal. This means that it is able to follow any instruction of the controller provided that it remains within the battery constraints 3 and 4. Regarding the battery model, charging and discharging efficiencies are assumed to be 100%, and no leakage phenomenon is considered.

5.2 Control algorithm

Like in previous scenarios, controller looks at boilers in case they are at their lower limits. Once this specific case is handled, excess power is supplied to boilers first and battery second. In the case of a negative excess

or demand, the battery supplies the demanded power provided that such demand lies within the battery constraints. If that is not the case, the remaining demand is absorbed by the main grid. Algorithm 3 presents the control logic implemented in Scenario 3.

Algorithm 3: Scenario 3: control of boilers and battery

Executed every time-step h

Inputs: $\hat{T}_B[h], p_{PV}[h], p_{nc}[h], \hat{s}_B[h - 1], x_b[h]$

Control variables: \hat{u}_B, 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

$\hat{u}_B \leftarrow 0, u_b \leftarrow 0$

$p_x = p_{PV}[h] + p_{nc}[h]$

sort $\hat{T}_B[h]$ in ascending order

for each boiler k **do**

if $T_{B,k}[h] \geq T_{\Delta,k}$ **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**

$| u_{B,k} \leftarrow \bar{P}_{B,k}$

$| p_x = p_x + u_{B,k}$

end

end

if $p_x \geq 0$ and $s = 0$ **then**

for k **do**

$| e_k[h] = \max[0, (\bar{T}_{B,k} - T_{B,k})]$

$| u_{B,k} \leftarrow \max[-C_w \frac{e_k[h]}{\Delta t}, \bar{P}_k, \min(-p_x, 0)]$

$| p_x = p_x + u_{B,k}$

end

$u_b \leftarrow \max[\frac{x_b[h] - \bar{C}_b}{\Delta t}, \bar{P}_b^{ch}, \min(-p_x, 0)]$ (charge battery)

else

$u_b \leftarrow \min(\frac{x_b[h] - \bar{C}_b}{\Delta t}, \bar{P}_b^{disch}, -p_x)$ (discharge battery)

end

update Control variables

End

5.3 Limitations

The incorporation of a battery system is able to tackle one of the limitations of previous scenarios and therefore increase self-consumption. However, it also introduces a new challenge for future scenarios, which is

to improve the battery model. Important parameters such as charging and discharging efficiencies as well as battery leakage coefficient have not been considered in the present scenarios. By implementing a better model, a more precise control action could enhance battery usage and make the EMS more realistic.

The list of limitations is summarized below:

- Inter-interval power variations are not accounted by the controller.
- Very basic modelling of boiler's temperature evolution.
- Very basic modelling of battery's SoC evolution.

6 Scenario x

(nevermind)

In order to take into account the dynamics of boilers, a more detailed model than the one presented in Equation 1 is needed.

The hot water tank is modelled as a volume of water with a homogeneous temperature, across the whole tank. Its temperature variation is not only a function of the power input, but also of the hot-water consumption. The discret equation can therefore be expressed as:

$$T_{wh}[h+1] = e^{-\frac{dt}{R_h C}} T_{wh}[h] + (1 - e^{-\frac{dt}{R_h C}}) R_h u_{ewh}[h] \\ + (1 - e^{-\frac{dt}{R_h C}}) R_h [U \quad d_w^h] \begin{bmatrix} T_a[h] \\ T_c[h] \end{bmatrix}$$

where C is the water tank thermal capacity, $R_h = (U + d_w^h)^{-1}$ is the equivalent water-to-exterior resistance that takes into account the thermal losses U and water withdrawal d_w^h at time instant h . T_a and T_c stand for the ambient air temperature and the inlet cold water, respectively. The efficiency of the electrical system is assumed to be 1. d_w^k is the water drawn from the k^{th} hot water tank (l/s).