Microgrids

ELEN0445

From real-time control to sizing

Introduction


Load
3.0 K
2.5 K
2.0 K
1.5 K
1.0 K
500
0
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00
L1 Load
Load
2.5 K
2.0 K
1.5 K
1.0 K
500
0
L2 Load
Load
4.0 K
3.0 K
2.0 K
1.0 K
0
L3 Load

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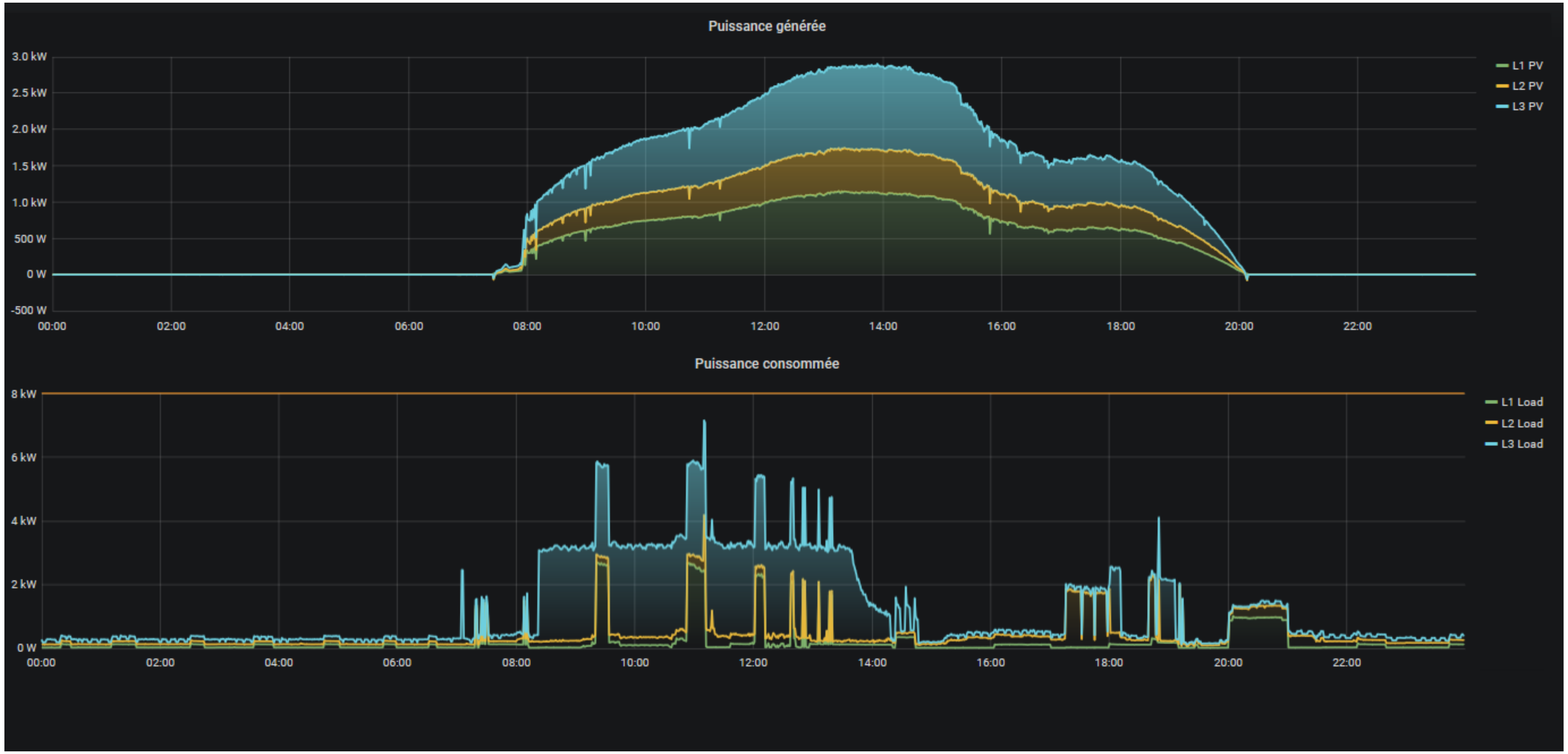
Sciences Appliquées



Puissance générée
3.0 kW
2.5 kW
2.0 kW
1.5 kW
1.0 kW
500 W
0 W
-500 W
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
L1 PV
L2 PV
L3 PV
Puissance consommée
8 kW
6 kW
4 kW
2 kW
0 W
L1 Load
L2 Load
L3 Load

Content of this lecture

- We take the role of the operator of the microgrid, who wants to optimize the way the energy is produced and used within the microgrid, and to optimize the interaction with the public grid (simple interaction, e.g. varying price).
- We make the assumptions that the microgrid is single-user, and we also avoid the question of the “fast dynamics” of the components of the microgrid.

Reminder: control levels

Level	Function	Examples
1	Device level control	BSS control, reactive control
2	Local area control	Frequency regulation, fast load shedding
3	Supervisory control	Forecasting, operational planning
4	Public Grid interaction	Ancillary services, energy markets

We will be mainly focused on levels 3 and 4, and a bit about level 2

Level 1: device level control

- Generator control
- PV panel + MPPT + inverter
- A great variety of interfaces for loads.
- Battery storage: battery management system (BMS)
- Battery inverter/charger
- Islanding detection: Automatic transfer switch

Level 2: local area control

- Fast automatic load/generation control to ensure constant balance and achieve stable operating points:
  - regulate active and reactive power in AC microgrids
  - achieving stable operation may be a challenging problem because of:
    - dynamic response mismatches between loads and sources,
    - generated power capacity close to nominal load,
    - reduced added energy storage in generator rotors (if any).
- (Unplanned) disconnection management
- Resynchronization

Level 3: supervisory control

- Generation and load dispatch
- Economic optimization
- Spinning reserve
- Forecasting
- Data visualization and data management

Level 4: public grid interaction

- Distribution Management System interaction
- Electricity markets
- Ancillary services markets

Note: centralized vs decentralized control

- Centralized controller: controls power flow from each source and monitors overall system condition
- Fully decentralized – also called autonomous – control strategy :
  - prevent potential system outages, as may happen if the controller fails in a centralized scheme.
  - make decisions without communicating with other system components by estimating system conditions from locally measured variables
  - More complex to implement than centralized => more risk of “bug”
- Some decentralized control schemes require a communication link among their **distributed** controllers in order to coordinate their actions.
  - reduces control complexity, but decreases reliability

In this lecture: level 3 & centralized control

Real-time control

- As often as possible, solve an optimization problem to optimize the power dispatch among the devices.
- Take into account the measured state of the system
  - Technical state: output power of a generator with ramping constraints, state of a storage system
  - Market-related state: nominated injection/withdrawal from the grid, peak penalty, i.e., capacity fee, reserve level to maintain
- Either as a « **static** » problem or considering a few time steps to include dynamics if necessary (e.g., ramping), i.e., depending on the frequency of the optimization.

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Very-short term forecasts

- Cameras filming the sky
    - Chow, Chi Wai, et al. "Intra-hour forecasting with a total sky imager at the UC San Diego solar energy testbed." *Solar Energy* 85.11 (2011): 2881-2893.
- Short term wind forecasts
- Spatially correlated forecasts

Fig. 2. TSI 440A Total sky imager.

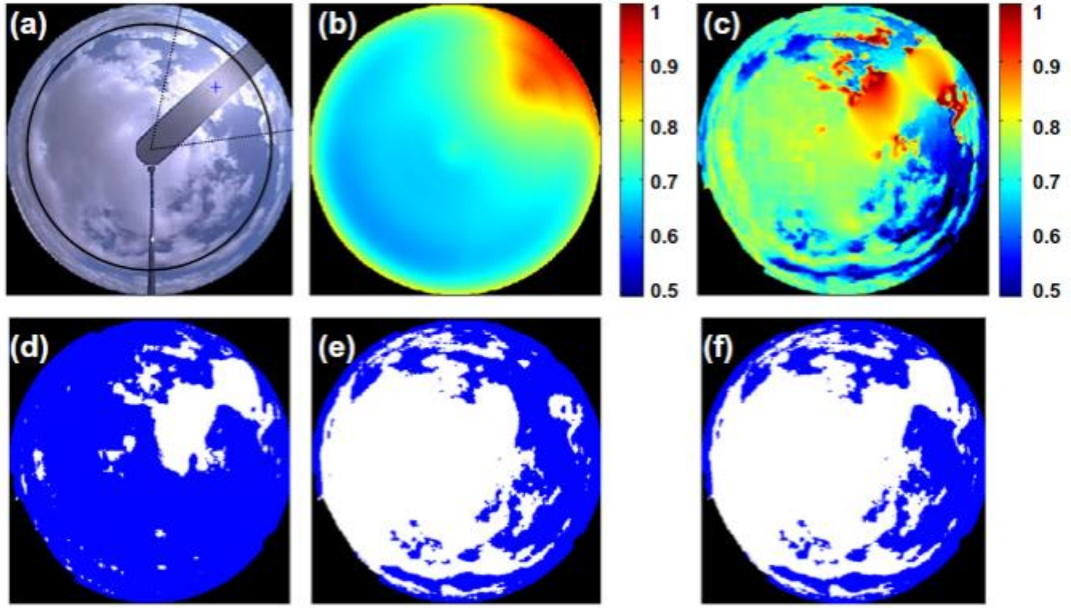

Fig. 3. Processing chain of a sky image on October 4, 2009 15:45:30 PST (a) to obtain the cloud decision image. The sunshine parameter is 0.85 and is evaluated around the sun position indicated by the blue cross. The dotted black lines show the borders of the circumsolar region defined as solar azimuth ±35° and the solid black line shows ZA at 65°. (b) Clear sky RBR (colorbar) background image plus the threshold. (c) RBR (colorbar) image. (d) Pixels in (c) with RBR > SP (d) or (e) RBR > CSL threshold (e) are assumed to be cloudy. (f) Shows the final cloud decision image. White areas are clouds and blue areas are clear skies.

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Presentation of (a part of)

Dumas, Jonathan, et al. "Coordination of operational planning and real-time optimization in microgrids." *Electric Power Systems Research* 190 (2021): 106634.

(I advise you to read this paper).

Stating an optimization problem

In that order, define

1. The parameters, i.e. data
2. The sets (and indices)
3. The optimization variables
4. The objective function
5. The constraints

Real-time problem statement

- We have
  - Sets of devices that consume, generate, or store electricity, with their technical constraints
  - a connection to the grid, with import and export limits
  - costs related to energy imports, fuel, the *value of lost load*, storage usage
  - revenues from energy sold to the grid, ancillary services provision (not considered in the sequel)

$\mathcal{D}^{sto}, \mathcal{D}^{she}, \mathcal{D}^{ste}, \mathcal{D}^{nst}$

E_t^{cap}, I^{cap} [kW]

γ^{sto} π^i π^e π^{ste} π^{she}

The current operation point is measured or estimated

- Import/export status
- Generation of devices
- State of charge of batteries
- Real-time limitations of devices (e.g. power as a function of SoC, typically provided by the BMS)

Goal

- Minimize instantaneous and delayed costs
- Subject to
  - Power balance
  - State evolution
  - Technical limits of devices
  - Available renewable generation
  - Load and its flexibility

Actions

$$0 \leq a_d^k \leq 1 . \quad \forall d, \forall k .$$

- Steerable generation: power output $= a_d^{ste} \cdot \overline{P}_d$
- Non-steerable generation: power output $= (1 - a_d^{nst}) \, \overline{P}_d^{nst}$

  e.g. measured PV gen

- Sheddable load: power consumed $= (1 - a_d^{she}) \, C_d^{she}$

  power user would like to consume

- Charge and discharge:

  $$P_d^{che} = a_d^{che} \cdot \overline{P}_d^{che} \qquad P_d^{dis} = a_d^{dis} \cdot \overline{P}_d^{dis}$$

Storage dynamics

$\eta_d \in [0,1]$: efficiency

$$S_{d,t+\Delta t} = \hat{S}_{d,t} + \left(P_d^{cho}\,\eta_d^{cha} - P_d^{dis}/\eta_d^{dis}\right)\Delta t .$$

measured / estimated

In reality function of
- temperature
- SoC
- power.

(Embeds converter's η).

Storage limits

$$\underline{S}_d \leq s_{d,t+\Delta t} \leq \overline{S}_d \qquad \forall t,\ \forall d \in \mathcal{D}^{sto}.$$

if $\hat{s}_{d,t} \notin [\underline{S}_d, \overline{S}_d]$?

$\Rightarrow$ force charge or discharge to go into bounds

may be $\emptyset$ if $\overline{P}^{dis}$ or $\overline{P}^{cha}$ too small.

How would you do this ?

Instantaneous cost

$$C = \pi^{i} i^{gri} - \pi^{e} e^{gri} + \Big(\sum_{d \in D^{ste}} \pi_d^{ste} a_d^{ste} \bar{P}_d + \sum_{d \in D^{she}} \pi_d^{she} a_d^{she} C_d^{she}$$

$$+ \sum_{d \in D^{nsl}} \pi_d^{nsl} a_d^{nsl} P_d^{nsl}$$

lost opportunity

$$+ \sum_{d \in D^{sto}} \gamma_d^{sto} \left(\bar{P}_d \eta_d^{cha} a_d^{cha} + \underline{P}_d a_d^{dis} / \eta_d^{dis} \right) \Big) \Delta t$$

Delayed costs

$$D = \pi^{peak} S_{peak}$$

$$\hat{i}^{\,gu}_{0:t} + \left(i^{gu}_0 - e^{gu}_0\right)/\Delta t \leq peak$$

$$S_{peak} \geq peak - \underbrace{\text{historic peak}}_{\text{param}}$$

params.

Feasibility problem

- The measured state may be out of the limits that are set
- Example: the measured SoC of a battery is 99.5%, but it should be <= 99%
- Relax constraints and add a large enough penalty term in the objective
  - Large enough -> function of the criticality of the constraint violation

Side goals

- Avoid changing set-points too frequently
  - Add a regularization term in the objective, e.g., a norm of the action to take minus the previous action. $\lambda \, \| \underline{a} - \underline{a}_{previous} \|$
  - How to choose the weight of the penalty term?
    - Too high -> smooth but not reactive
    - Too low -> useless

Storage model and usage fee

- The battery will degrade as it gets used.
- Classical model to estimate degradation: energy throughput.
- In short-term operation, you should use storage only if gain > degradation.
- Hence a “virtual” storage fee to avoid a usage that seems profitable in the short run but detrimental overall.
- In a sizing procedure, the actual cost of the storage device and max number of cycles will be taken into account, so there will be no need for a fee.

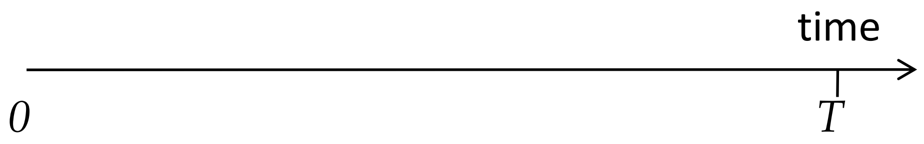
Operational planning

When are operation decisions taken?

- It can be in real time: corrective decisions
- Or in anticipation: **preventive** decisions
- Why should we anticipate? because of time coupling constraints:
  - The typical periodicity of renewable generation devices and consumption is a day
  - Human activity has weekly and seasonal periodicity

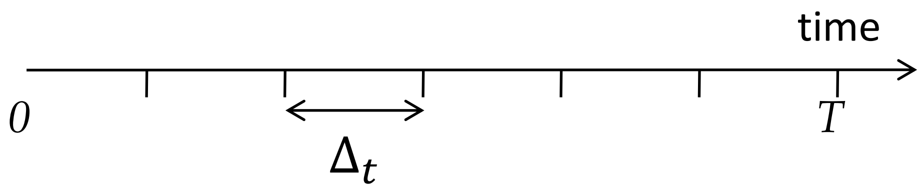
Operational planning decision horizon T

- We cannot take preventive operation decisions too much in advance:
- too high uncertainty on the evolution of the state of the microgrid and its environment
- anticipating a bit on the sequel, the problem we will have to solve may be intractable
- We thus consider operating the system over one day to approx. one week. This can be more or less, depending on the particular situation of the microgrid (type of storage, type of business activity, etc.)



Operational planning decision duration Δ_t

- For computational reasons, we **discretize** the decisions in time
- Depending on the decision horizon, we may consider periods of 1 to 15 minutes where decisions are assumed constant
  - Example: constant charge power for a battery
  - Determining good decisions may become intractable if we have too many decisions in the decision horizon
  - Forecasts may anyway not be meaningful with a too high temporal resolution
  - This is coherent with market period duration

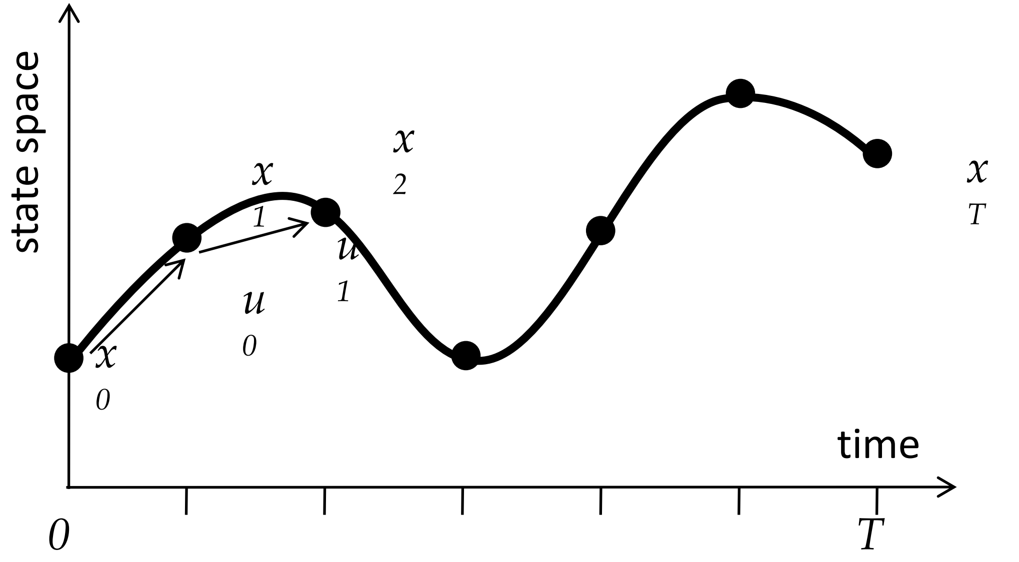


Operation as a sequential decision-making problem

We have a discrete-time system represented by a **state** x_t

$x = (x_0, x_1, \ldots, x_T)$ *represents the* ***state evolution*** *of the system*

$u = (u_0, \ldots, u_{T-1})$ *is a* ***sequence of control actions*** *(decisions)*



Given a criterion, we can compute an open-loop sequence of actions u^* to drive the system

We estimate demand, generation, availability of system components, etc. and then solve

minimize cost of u

subject to
1. balance generation and demand
2. dynamics: x_t, $u_t \longrightarrow x_{t+1}$
3. action sequence and state evolution restrictions
4. initial state x_0

Uncertainty

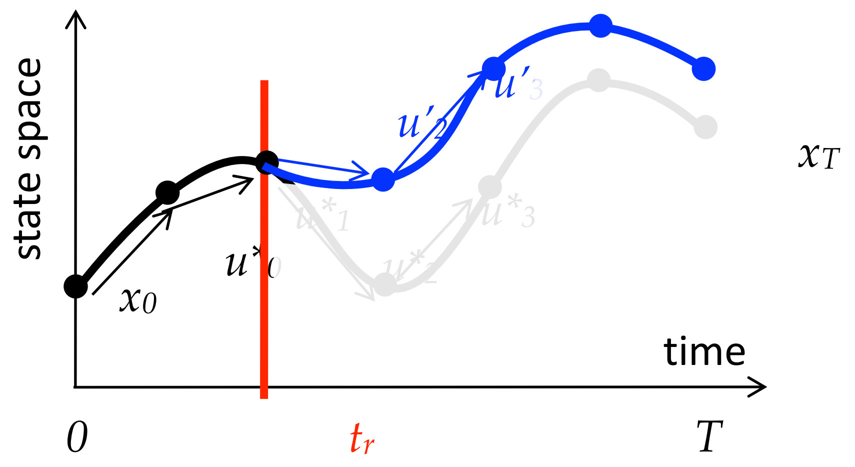
- Microgrid operation is impacted by factors that are not easily predictable
  - the weather, which impacts renewable generation and consumption
  - outages of steerable generation or storage
- Some events may thus turn the open-loop sequence u^* suboptimal or infeasible
- This can be mitigated by the a receding horizon approach

Receding horizon approach

Example: demand variation or restriction on x or u are observed at time t_r

Receding horizon approach: update the sequence of control actions

1. Re-estimate the parameters (demand, availabilities)
2. Re-solve the open-loop formulation



So, finally, when are decisions applied?

- Every time we solve the optimization problem above, we "freeze" some decisions:
  - not only the decisions for the decisions occurring before the next re-optimization
  - but also decisions that have a high impact on the interactions within the microgrid or with the public grid, and that span the whole decision horizon
- Hence, depending on the moment of the day, some decisions may or may not be re-optimized

Decisions, in practice

- Storage devices: Set point for charging / discharging
- Steerable generation
- Non-steerable renewable generation: curtailment
- Load shedding
- Load flexibility
- Power electronics

Remark: decisions we do not consider

We do not consider **investment decisions**

- This is the topic of another topic on sizing

We do not consider **maintenance decisions**

- Maintenance cost can be accounted for in sizing
- In operation, scheduled maintenance are just extra constraints or data updates (e.g. PV is out)
- If necessary, maintenance scheduling could be stated as an extension of operational planning

Constraints, in practice

- Capacity of devices
- Inverters constraints
- Demand-side management
- Generation management
- Regularization:
  - avoid changing decisions if unnecessary/undesirable

Optimization objectives

The invoice

- (In Belgium), the invoice of a user connected to a distribution network is composed of:
  - A part proportional to the energy consumed
  - A part proportional to the capacity of the connection, i.e. the amount of power the user can withdraw from the distribution grid
  - A part proportional to the "cos phi"
  - Taxes and other contributions
- This varies a lot as a function of the type of connection (i.e. of the voltage level and overall consumption)

Minimize the energy purchase cost

- The microgrid is subject to a dynamic price signal. At every time t, it can buy electricity at a price p_t
- Then, it will try to
  - consume & charge the storage devices during low price periods
  - produce & discharge the storage devices during high price periods
- Note: for now, we consider that
  - the microgrid cannot influence the price
  - there is no imbalance penalty
  - on the other hand, we will not always assume the price is known in advance.

Maximize the electricity sale price

- In a similar way, the price at which a retailer will buy back the energy can be described as a vector of prices, one per hour of the day.
- The sale price is obviously always lower than the purchase price:
  - because the retailer takes a margin
  - because the purchase price includes the grid fees, taxes, etc.
- There may be an injection fee depending on the DSO

Minimize the peak

- A grid user pays a monthly fee function of his peak quarter-hourly consumption over the last 12 months.

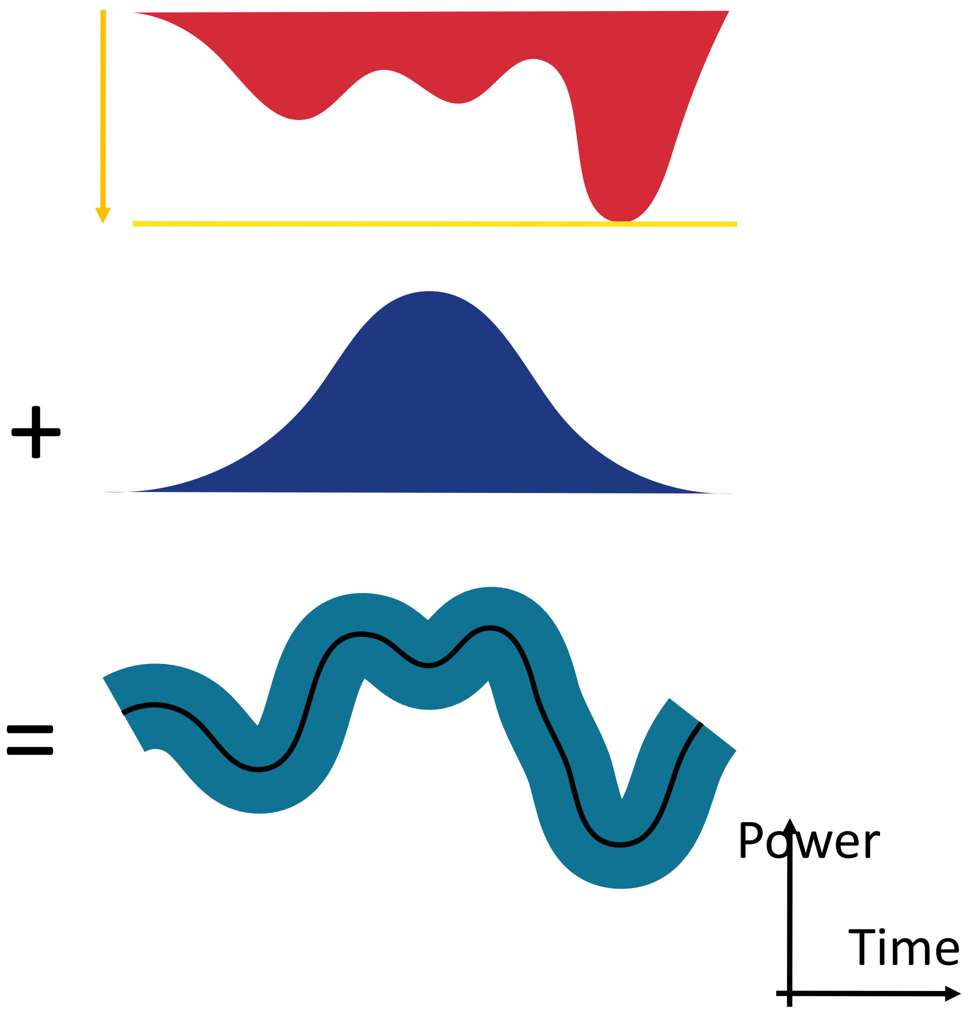
- Remark: this introduces a huge time coupling in the operation problem.

Maximize the reserve

- Keeping some reserve, i.e. some flexibility to quickly change the net position (total generation - total consumption) of the microgrid is important for two reasons:
  - It can be used to sell ancillary services to the grid
  - It can be used to stabilize the microgrid, in islanded mode.

In summary

- Costs
  - Energy consumption
  - Peak penalty
- Revenues
  - Energy production
  - Ancillary services



Minimize components’ degradation

- Generation devices, such as internal combustion machines, have a lifetime which varies significantly with the way they are used.
- Batteries suffer of the same problem. However, this depends a lot with the type of battery technology.

(Islanded mode) Ensure security of supply

In case of public grid service interruption, the objective of the microgrid may suddenly switch to simply keeping the critical loads powered as long as possible.

All these objectives are (most of the time) conflictual

- For instance:
  - Minimizing the peak can lead to opportunity losses with respect to low energy purchase prices
  - Maintaining a level of reserve can lead to peak increases and also to some opportunity losses with respect to energy purchase/sale price
  - Minimizing component degradation should be put in perspective with the opportunity losses it generates
- Hence we must **reach a tradeoff between these objectives**

Load models for demand-side management

What are the electrical devices in your house?

On the demand side

- Lights
- Fridges
- TV, computer, etc.
- Dishwasher
- Washing machine
- Tumble dryer
- Electrical vehicle
- Hot water boiler
- Heat pump
- Direct heating
- Pumps
- etc.

On the generation side: PV, …

+ storage

How can you characterize these loads?

- Power rating (kW, kVA, kvar)
- Power consumption pattern
- Energy consumption
- Efficiency
- Flexibility
- Controllability
- Behavior w.r.t. voltage variation, frequency variation

The next models are inspired from

- Roh, H. T., & Lee, J. W. (2015). Residential demand response scheduling with multiclass appliances in the smart grid. IEEE Transactions on Smart Grid, 7(1), 94-104.

Loads can be subdivided in 5 categories

- **E**lastic / **I**nelastic
- **M**emory**L**ess, with **F**ull **M**emory or **P**artial **M**emory
- Interruptible or **U**n**I**nterruptible

Set	Appliances
$\boldsymbol{A}_{EML}$	light bulbs with controllable brightness, electric fans with controllable speeds
$\boldsymbol{A}_{EFM}$	battery chargers (electric vehicles) with controllable charging rates
$\boldsymbol{A}_{EPM}$	electric heaters, air conditioners, refrigerators
$\boldsymbol{A}_{IEI}$	battery chargers (electric vehicles) with fixed charging rates, computers with int
$\boldsymbol{A}_{IEUI}$	washing machines, dishwashers, electric ovens, televisions, light bulbs without

A model is proposed for each category

- Let x_a^t be the consumption of appliance a at time t
- Let y_a^t be an integer variable that denotes whether appliance a starts at time t
- Parameters define limits on x_a^t (x_a^{min}, x_a^{max}), minimum performance thresholds of appliances' performance (R_a, R_a^t), energy consumption for inelastic ones (E_a), etc.

E.g. elastic with full memory loads (EFM)

Each appliance a also has the maximum and minimum values for its energy consumption, $x_a^{\max}$ and $x_a^{\min}$, respectively, at each sub-interval t, that is

$$x_a^{\min} \leq x_a^t \leq x_a^{\max}, \quad \forall t \in \boldsymbol{T}_a, \ \forall a \in \boldsymbol{A}_{\mathrm{EFM}}. \tag{10}$$

Each appliance a has its utility function $U_a(\boldsymbol{x}_a)$, which is defined as

$$U_a(\boldsymbol{x}_a) = U_a\left(\sum_{t \in \boldsymbol{T}_a} x_a^t\right), \quad \forall a \in \boldsymbol{A}_{\mathrm{EFM}}. \tag{11}$$

(…)

We also assume that the utility function is a concave function. In addition, we assume that for each appliance a, its user has the following requirement:

$$U_a(\boldsymbol{x}_a) \geq R_a, \quad \forall a \in \boldsymbol{A}_{\mathrm{EFM}}. \tag{12}$$

This requirement indicates that the performance of appliance a that depends on its total energy consumption should be higher than or equal to its minimum threshold R_a. We define the energy scheduling constraint of appliance $a \in \boldsymbol{A}_{\mathrm{EFM}}$ as

$$X_a = \left\{ \boldsymbol{x}_a \middle| \begin{array}{l} U_a\left(\sum_{t \in \boldsymbol{T}_a} x_a^t\right) \geq R_a, \ \forall t \in \boldsymbol{T}_a \\ x_a^{\min} \leq x_a^t \leq x_a^{\max}, \end{array} \right\}, \ \forall a \in \boldsymbol{A}_{\mathrm{EFM}}. \tag{13}$$

Overall problem

$$
\begin{aligned}
\underset{\boldsymbol{x}}{\text{maximize}} \quad & \mathrm{NU}(\boldsymbol{x}) \\
\text{subject to} \quad & \sum_{a \in \boldsymbol{A}} x_a^t \leq E_{\mathrm{th}}^t, \quad \forall t \in \boldsymbol{T} \\
& \sum_{t \in \boldsymbol{T}} \sum_{a \in \boldsymbol{A}} \lambda^t x_a^t \leq C_{\max} \\
& \boldsymbol{x}_a \in X_a, \quad \forall a \in \boldsymbol{A}.
\end{aligned} \tag{28}
$$

$$
\mathrm{NU}(\boldsymbol{x}) = \sum_{a \in \boldsymbol{A}_{\mathrm{EML}} \cup \boldsymbol{A}_{\mathrm{EFM}} \cup \boldsymbol{A}_{\mathrm{EPM}}} w_u U_a(\boldsymbol{x}_a) - w_c \sum_{a \in \boldsymbol{A}} \sum_{t \in \boldsymbol{T}} \lambda^t x_a^t \tag{27}
$$

Results

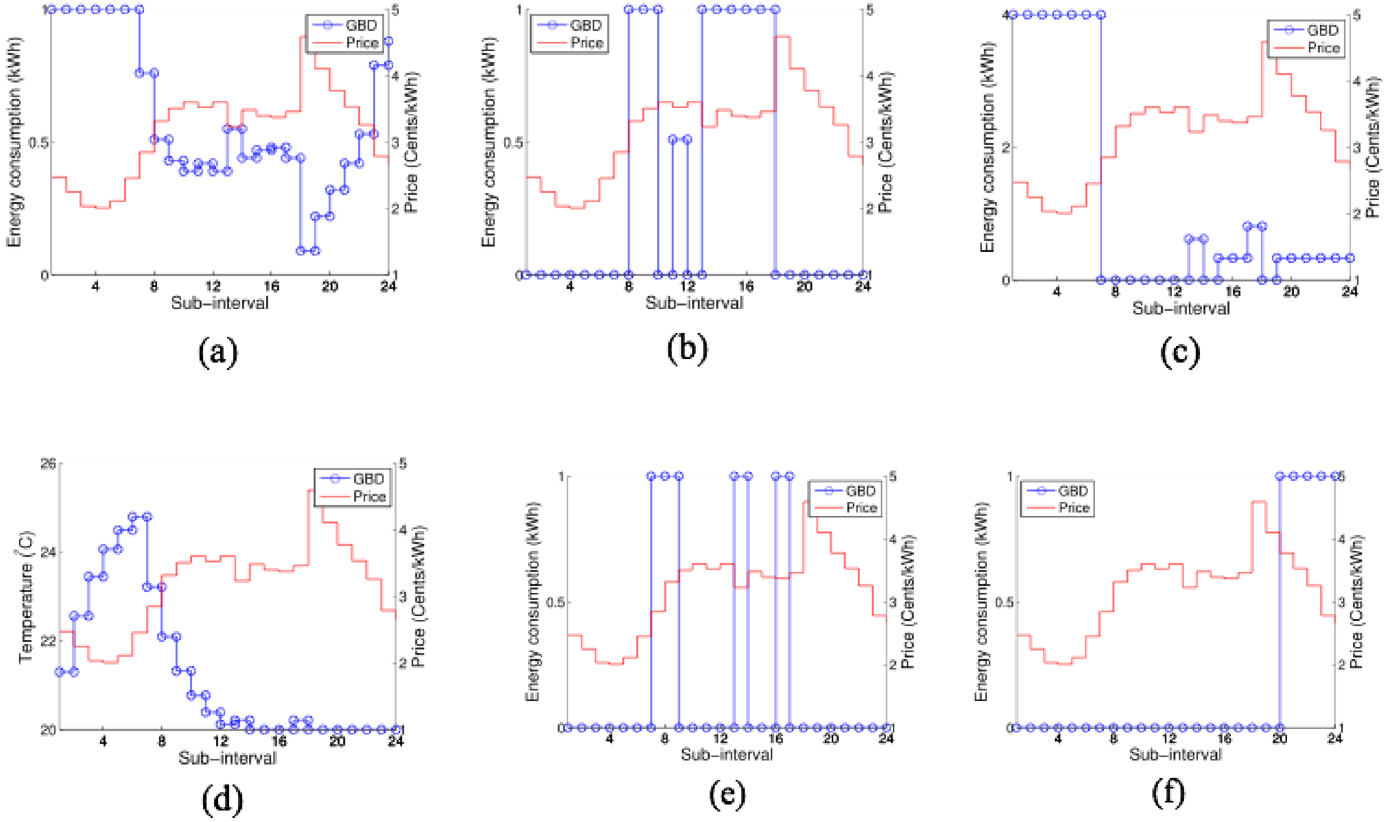


Fig. 2. ECS of the appliance in each set. Elastic appliance with a (a) memoryless property, (b) full memory property, and (c) partial memory property. (d) Temperature of elastic appliance with a partial memory property. Inelastic appliance with an (e) interruptible operation and (f) uninterruptible operation.

What is microgrid sizing

- Given information of a site
- consumption (energy and power)
- renewable generation potential (incl. land size, available rooftops, etc.)
- availability of a public grid
- budget constraints (maximum investment, ROI, etc.)
- reliability requirement

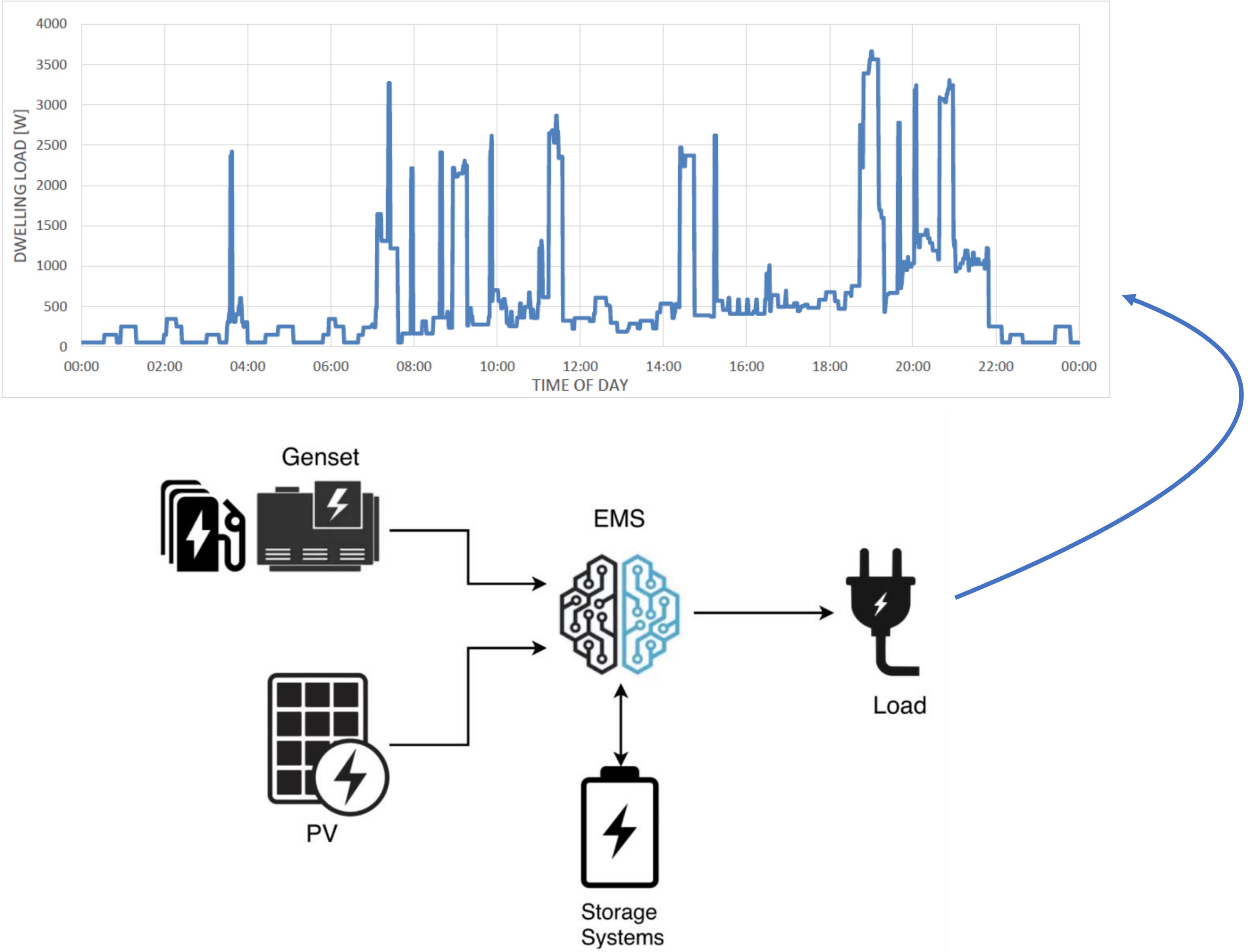
- Determine the best migro-grid design
  - which components?
  - which ratings?
  - (which network topology?)

Agenda

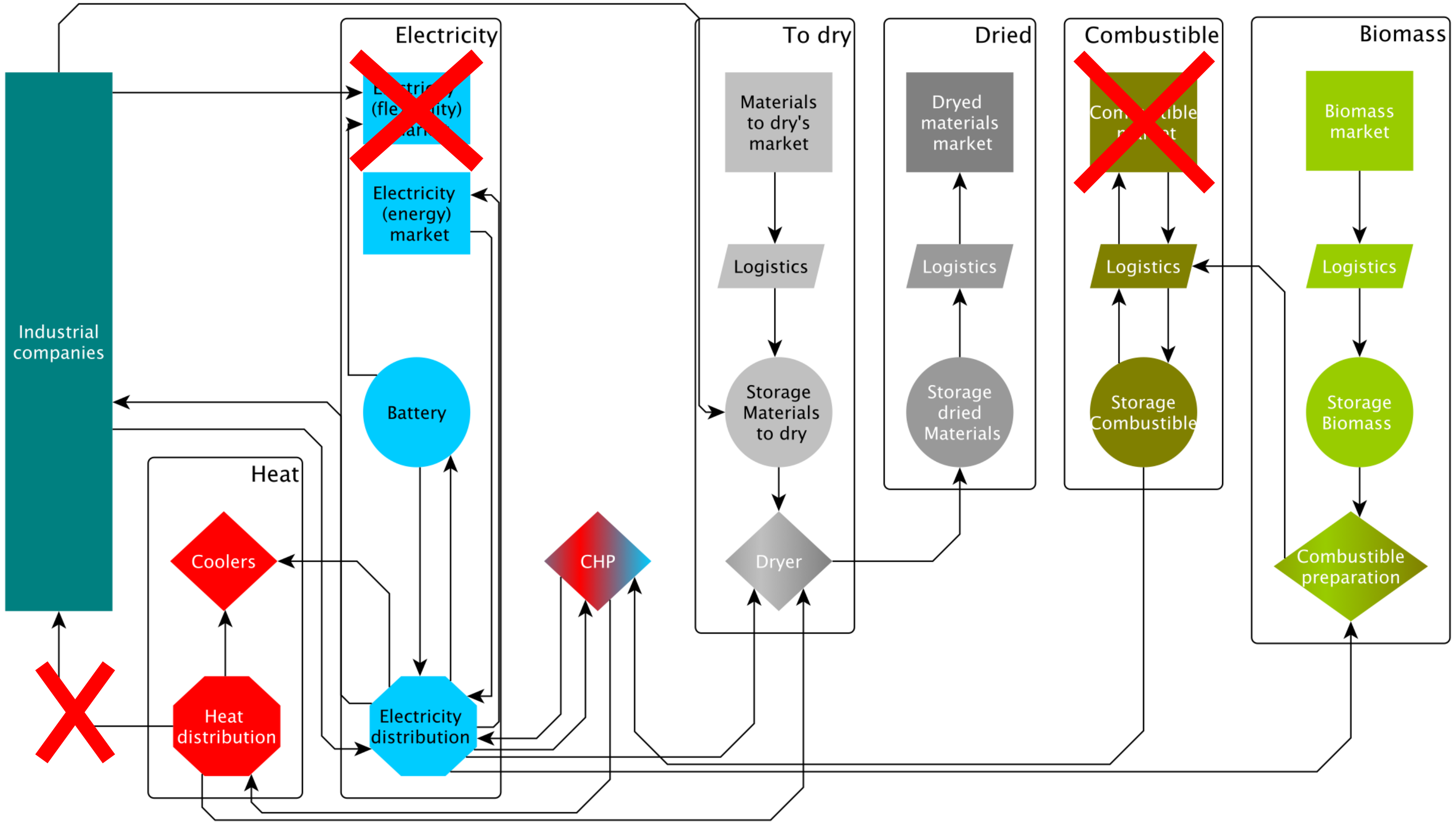
1. Use cases
2. What are the criteria that we should optimize?
3. How do we solve the problem?
4. Use case results

Examples

Use case 1: Off-grid microgrid



Use case 2: A CHP project



Use case 3: Accounting for storage degradation and reinvestment

Dakir, S., & Cornélusse, B. (2020). **Combining optimization and simulation for microgrid sizing**. Technical report.

TABLE I: Input parameters.

PV cost	800 €/kWp
BESS cost	300 €/kWh
η^{charge}, $\eta^{\text{discharge}}$	95 %
N	25 years
n	2 %
Δ_t	1 h
$\lvert\mathcal{T}\rvert$	24 h
$I^{\max}$, $E^{\max}$	1600 kW

- Battery degrades as a function of the number of cycles.
- After 3500 cycles, the residual capacity of the BESS is 70%.
- A reinvestment must be done.

Techno-economic and sizing principles

What is this section for?

- Making an investment is always a tradeoff between costs, benefits, value, risk, etc.
- The value of money varies with time
- Investing requires a financing scheme (e.g. a constant annuity loan)
- Besides the technical constraints, it is thus key to determine
  - Which financial objective to optimize (e.g. minimize costs?)
  - Whether the investment can be funded
  - How to present results from a financial perspective

Time-value of money

- The value of money evolves with time t as a function of (mainly) three factors:
  - the inflation rate d_t : the reduction of purchase-power of money (when $d > 0$)
  - the loan rate l_t
  - the interest rate i_t (for the cash you have on your bank account)
- Usually we have $d_t < i_t < l_t$
- Example: value in n years of money on your bank account $= \frac{(1+i)^n}{(1+d)^n} \times$ value now

Inflation rate

Source: http://www.inflation.eu/inflation-rates/belgium/historic-inflation/hicp-inflation-belgium.aspx

Economic evaluation based on the cost of electricity

- COE = CAPEX + OPEX

- Remarks:
  - More accurate if we consider the net present value, accounting for time value of money
  - Value of reliability should also be accounted for to rank several options.

Capital expenditure – CAPEX

The CAPEX in EUR/kWh is defined as

$$CAPEX = \frac{TIC\ FCR}{8760h\ CF}$$

with

- TIC [EUR/kW] the total installation cost divided by the rated power of the installation
- FCR the fixed charge rate, accounting fot the time value of money
- CF the charge factor, i.e, the fraction of the year the system is operating af the rated power.

Fixed charge rate (FCR)

- In its simplest form, it is equal to the inverse of the number of years over which the investment is amortized
- But in principle represents “the percentage of capital costs that must be recovered each year in order to cover all investment costs, including return on debt and equity.”*
  - Accounting for the time value of money, tax rebates, depreciation method, etc.

*T.E. Drennen and J. Andruski, “Power systems life cycle analysis tool (Power LCAT)”, U.S. National Energy Technology lab, DOE/NETL-2012/156,6, May 2012.

Operational expenditure – OPEX

- All the costs and revenues of the microgrid after the investment is made
- Should also include maintenance costs

The Total life cycle cost – TLCC

- Total cost over the microgrid life cycle taking into account:
  - The investment and reinvestments costs
  - Operating & maintenance costs
  - A discount cash flow factor
- Good financial indicator to be minimized in the case of an off-grid microgrid.

The Net Present Value – NPV

$$NPV(c,\lambda) = \sum_{t=0}^{N} \frac{\overbrace{-I_t(c_{[t]})}^{\text{Investment cost}} + \overbrace{R_t(c_{[t]}, a_{[t]})}^{\text{Revenues}} - \overbrace{O_t(c_{[t]}, a_{[t]})}^{\text{Operating cost}}}{\underbrace{(1+d)^t}_{\text{Discount factor}}}$$

- This indicator has the same parameters as the TLCC with the addition of revenues.
- Good financial indicator to be maximized in the case of a grid-tied microgrid.
- The NPV becomes positive when the payback period is within the lifetime of the microgrid.
- In an off-grid case, the NPV is equal to the opposite of the TLCC.

LCOE

- The Levelized Cost of Electricity (LCOE) can be used to compare the costs of different energy production resources.

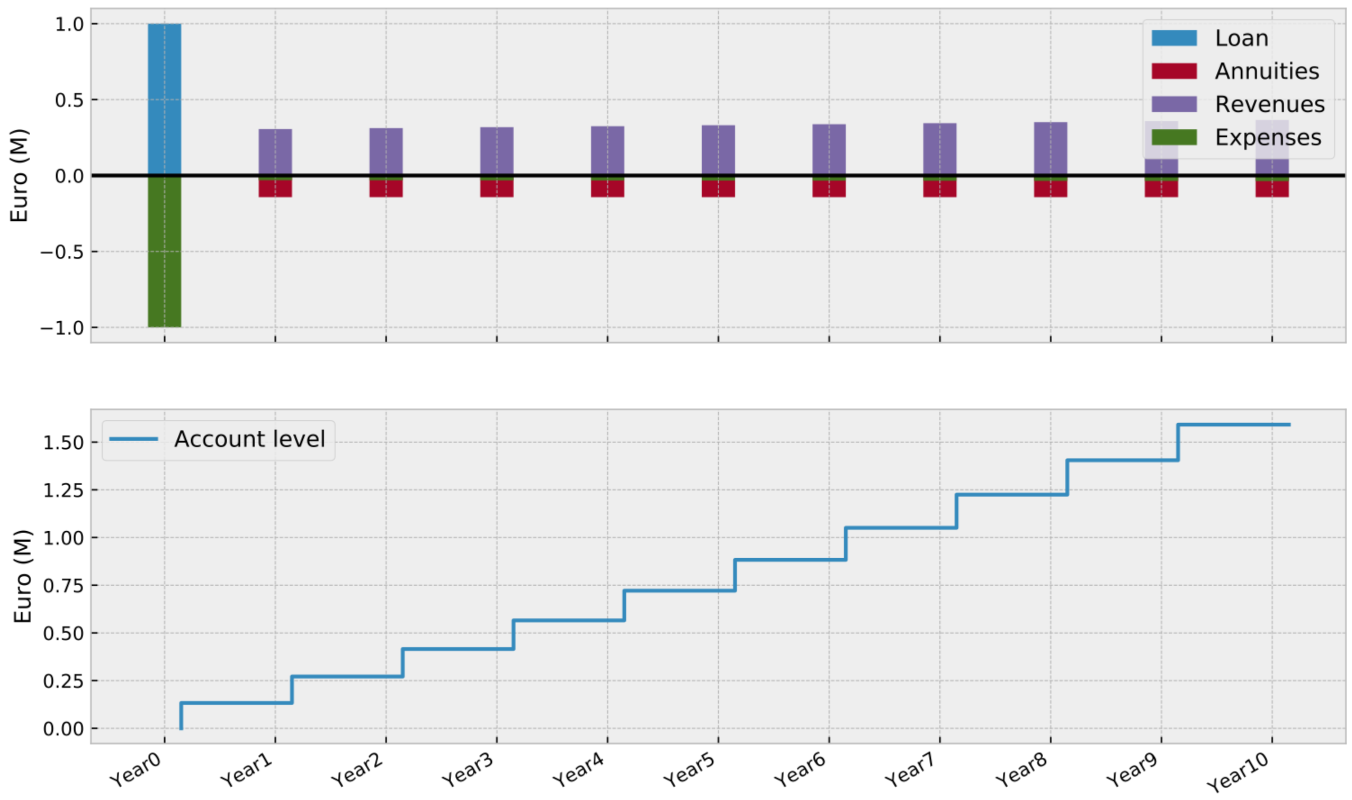
$$LCOE(c, \lambda) = \frac{\sum_{t=0}^{N} \frac{I_t(c_{[t]}) - R_t(c_{[t]}, a_{[t]}) + O_t(c_{[t]}, a_{[t]})}{(1+d)^t}}{\sum_{t=0}^{N} \frac{P_t}{(1+d)^t}}$$

How to present results?

Cash flow diagram

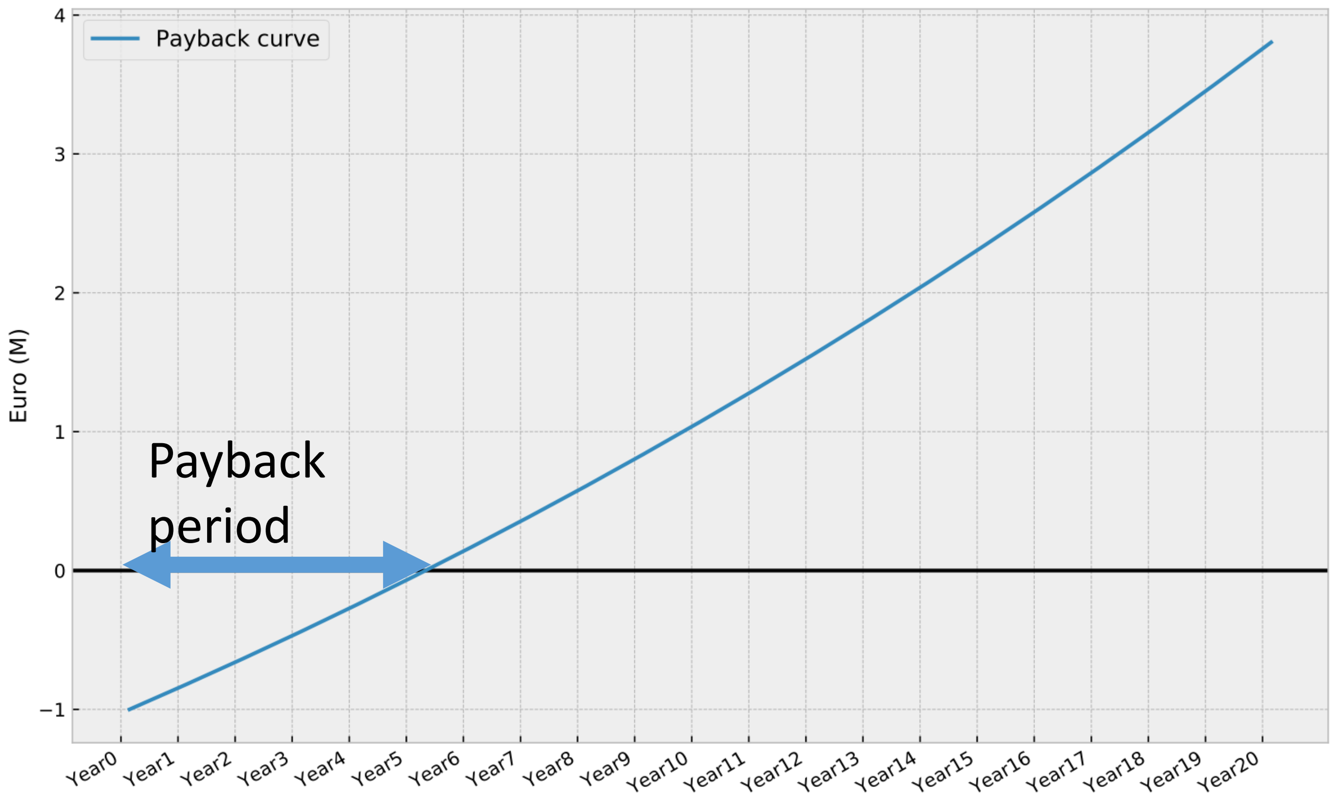
- A cash flow diagram describes how a budget evolves along time
- The cashflow representation depends on the role of an entity in a project
  - Microgrid entrepreneur borrows money, then spends money on equipment, then uses the assets, and pays back the money lender
  - The money lender (the bank), provides some cash, applies an interest rate, and waits for his money back
- We take the role of the microgrid entrepreneur

Cash flow diagram example



When are you “profitable”?

Return on investment



Solution methods

Simulation based

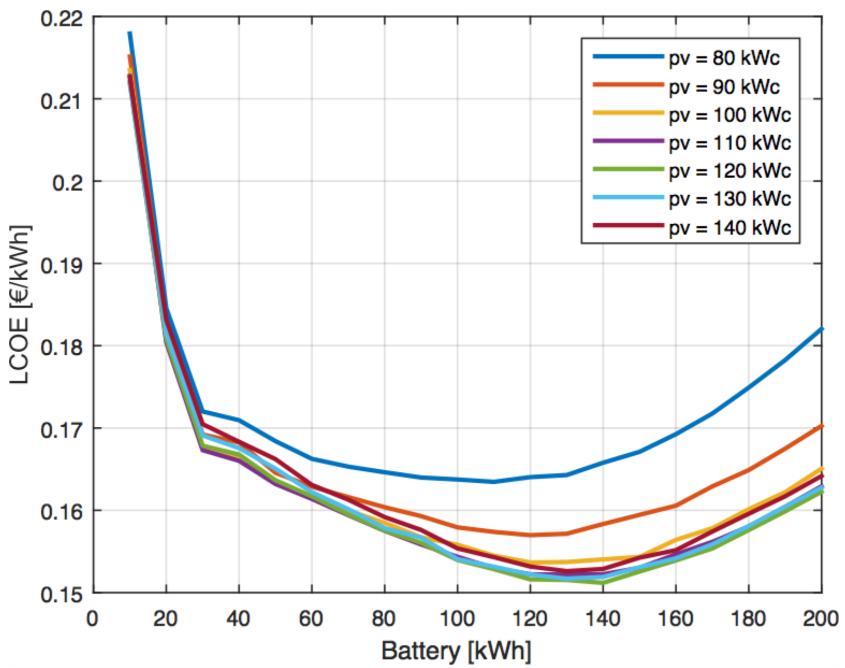
- Advantage of simulation:
  - It can easily incorporate non-linear models
  - a simulation is relatively fast
  - microgrids are relatively small systems, so not so many combinations to test
- Disadvantage:
  - when the interaction model with the grid is complex, requires to commit in advance, it is difficult to come up with an operational policy without operational planning, i.e. optimization
- E.g. [Homer software]

"At its core, HOMER is a simulation model. It will attempt to simulate a viable system for all possible combinations of the equipment that you wish to consider. Depending on how you set up your problem, HOMER may simulate hundreds or even thousands of systems.

HOMER simulates the operation of a hybrid microgrid for an entire year, in time steps from one minute to one hour."

Use case 1 – Battery + PV + genset

- Impose genset capacity to maximum demand



Optimization based

A two-level optimization problem **over the lifetime of the microgrid*** where **design decisions form the first level**, and operation decisions form the second level:

- min LCOE
- s.t.
  - CAPEX definition
  - OPEX definition
  - operational constraints

* Dakir, Selmane, Sélim El Mekki, and Bertrand Cornélusse. "On the number of representative days for sizing microgrids with an industrial load profile." *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. IEEE, 2020.

Use case 2 (...)

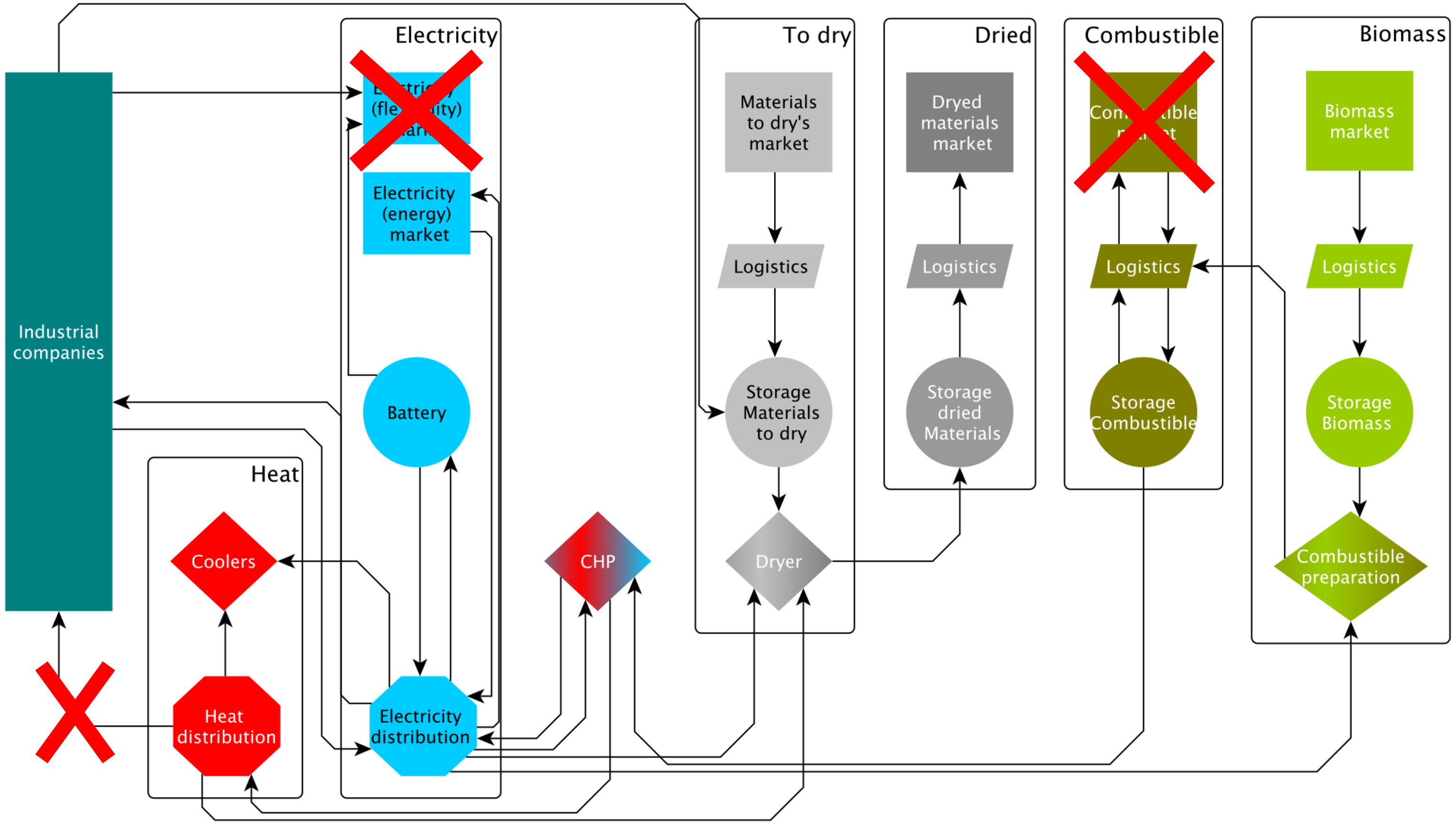
The system operation is modeled by a linear program:

- A process prepares the purchased biomass
- The prepared biomass supplies a cogeneration plant
- The heat is recovered in a drying process
- An "integral" constraint links the use of heat to the granting of green certificates (60% of the heat must be properly used to give rise to 1.6*1.5 green certificate per MWhe produced)
- Electricity supplies the auxiliaries (boiler, drying, cooler, fuel preparation).
  - The balance is sold (either to the market at 35 EUR/MWhe or to local industries at 77.5 EUR/MWhe).
  - Market import are possible (120 EUR/MWhe).

Use case 2’s linear program

- The main variables are the size of the installation
  - turbine
  - boiler
  - dryer
  - cooler
  - fuel preparation
- Auxiliary variables model the flows in 15-minute steps (market period for electricity)
  - they make it possible to express operating constraints (e.g. limit on the time variation of a given process)
- => The processes are linear: $\text{Out} = \text{alpha} \times \text{In}$

Use case 2: A CHP project



Constraints

- Constraint on the use of heat (granting of green certificates)
- Limit of variation of the CHP (0.8 MW / hour) upwards or downwards
- Logistics limits on the transport of raw materials, biomass, wet matter, dried matter
- The power plant and purchases cover the electrical consumption of auxiliaries, but the consumption of industries is satisfied in part if profitable

Key parameters

- green certificate price [65 EUR], number of green certificates [2.4]
- Spread between "purchase of dry material and resale of dry material" [0 to 4 EUR]
- Logistics limits [80 to 160 t/h] !!!!!
- Operating and maintenance costs [3% to 8%]
- Cost of purchasing biomass [0 to 30 EUR/t]
- The demand to serve

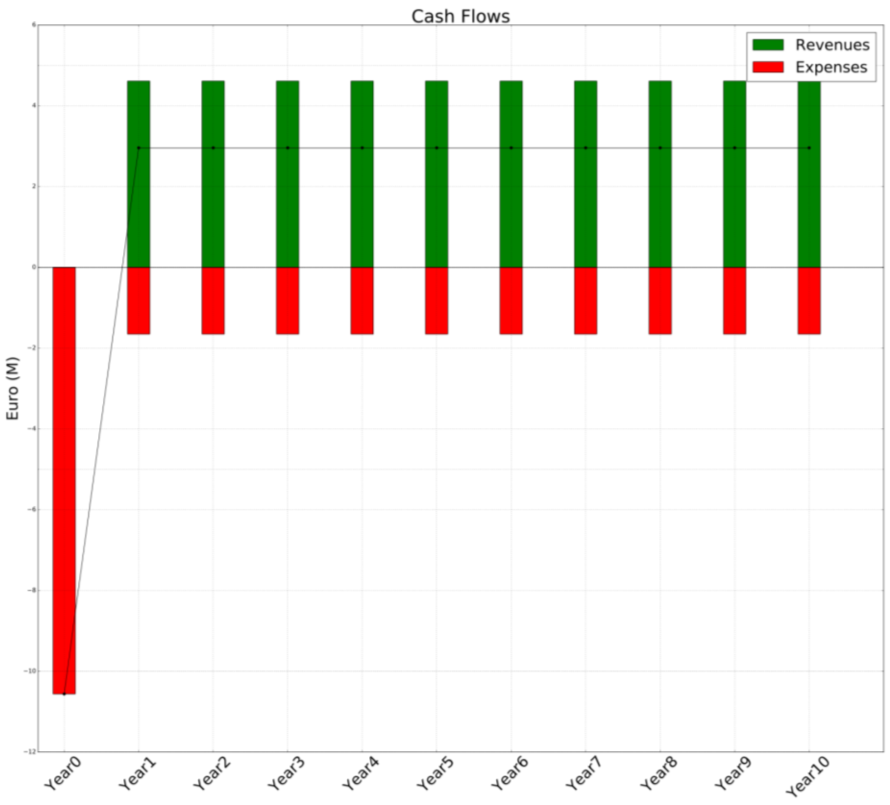
Use case 2 results

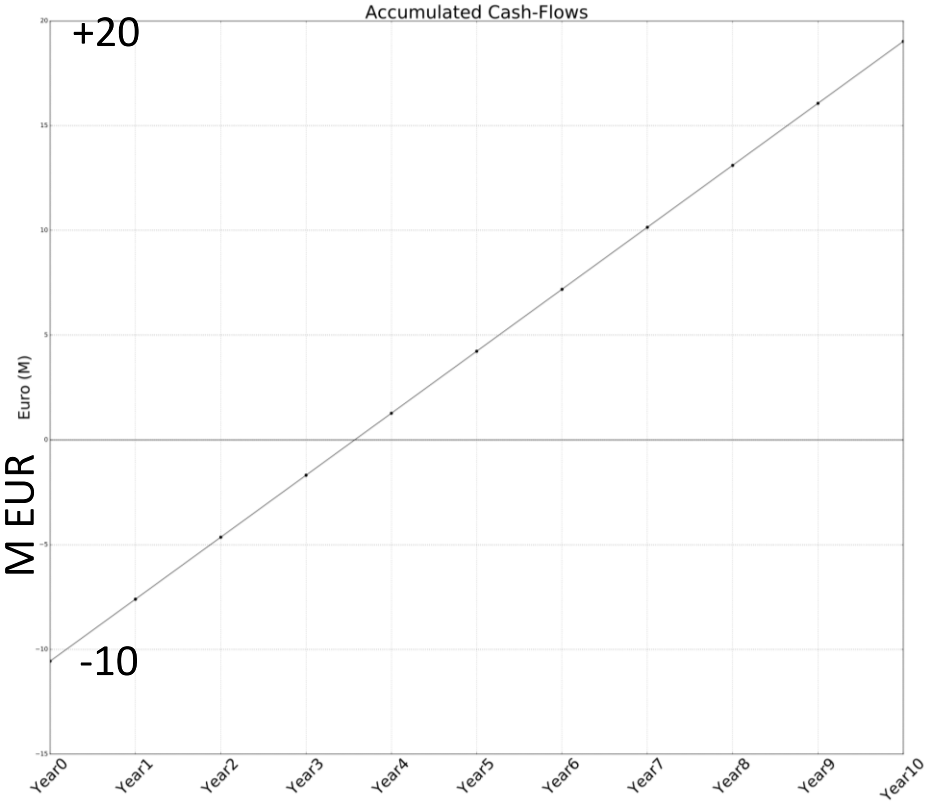
- Without satisfying industrial demand, the business case is profitable
- The big constraint is on the supply of the materials to be dried
- The optimal size of the plant is very sensitive to it
- E.g. Unfavourable scenario: biomass at 30 EUR/t, no drying gain (for the CHP operator), O&M at 8%
  - 80 t/h for m.p. => 3MWe cogen
  - 160 t/h => 6MWe

Caution

- We've probably overestimated efficiency parameters
- Some costs are neglected (engineering, network development, roads, storage, pollution control) => adds fixed costs mainly
- There is no forced shutdown period
- The quarter-hourly peak is not penalized (but very flat profiles and very little grid import).

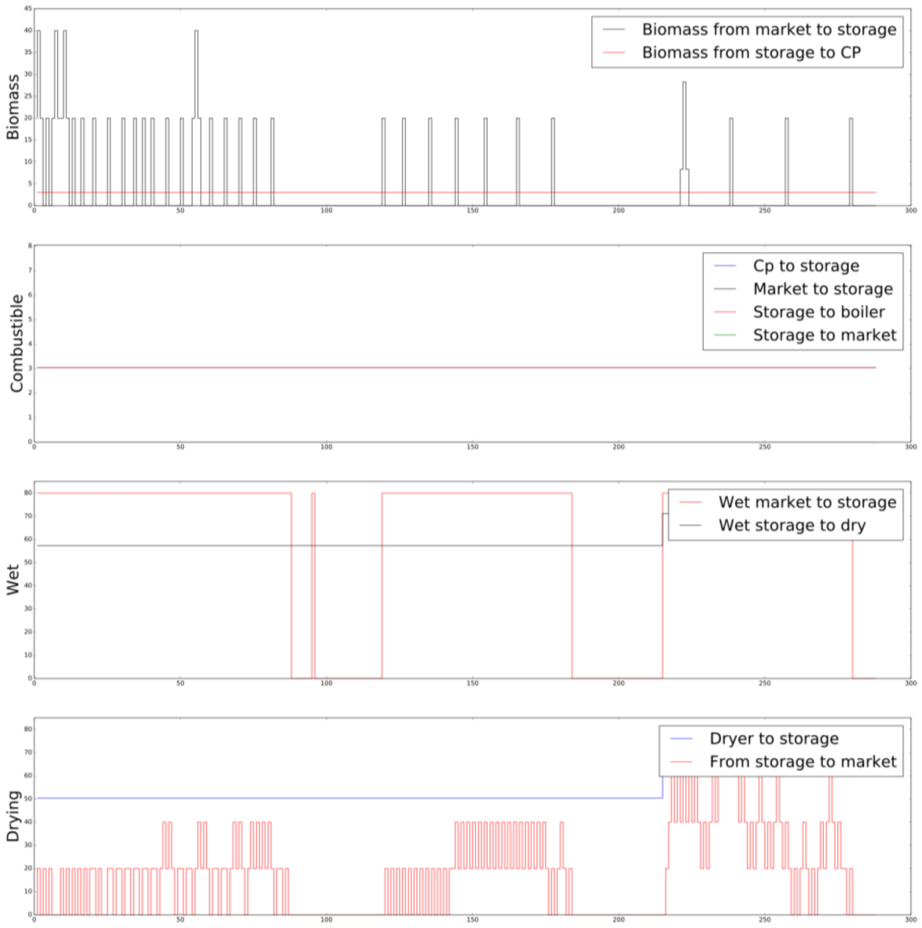
Unfavourable case: no external demand to satisfy, limit to 80t/h



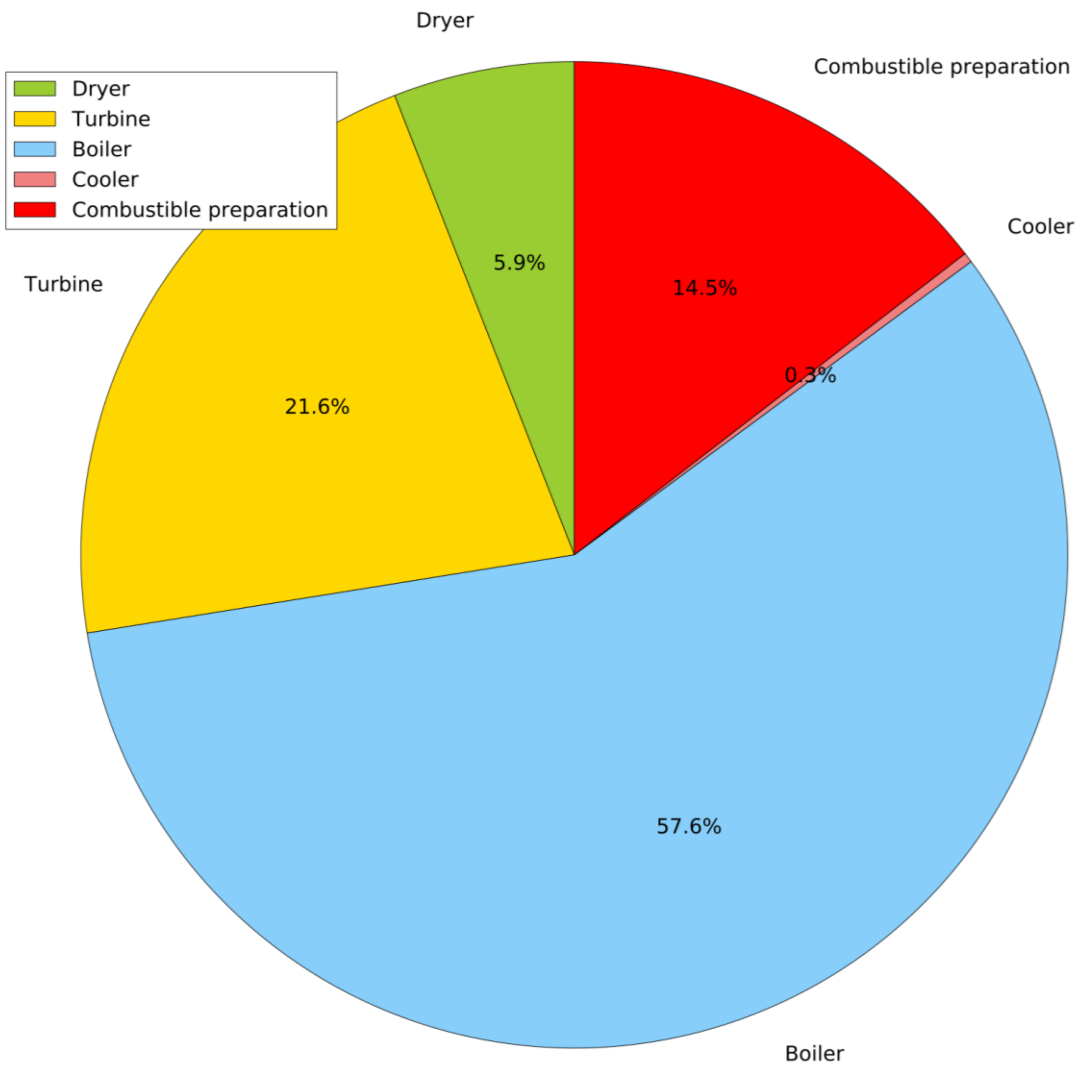


(...)


Dryer
Cooler
Heat


Biomass from market to storage
Biomass from storage to CP
Biomass
Cp to storage
Market to storage
Storage to boiler
Storage to market
Combustible
Wet market to storage
Wet storage to dry
Wet
Dryer to storage
From storage to market
Drying

(…)

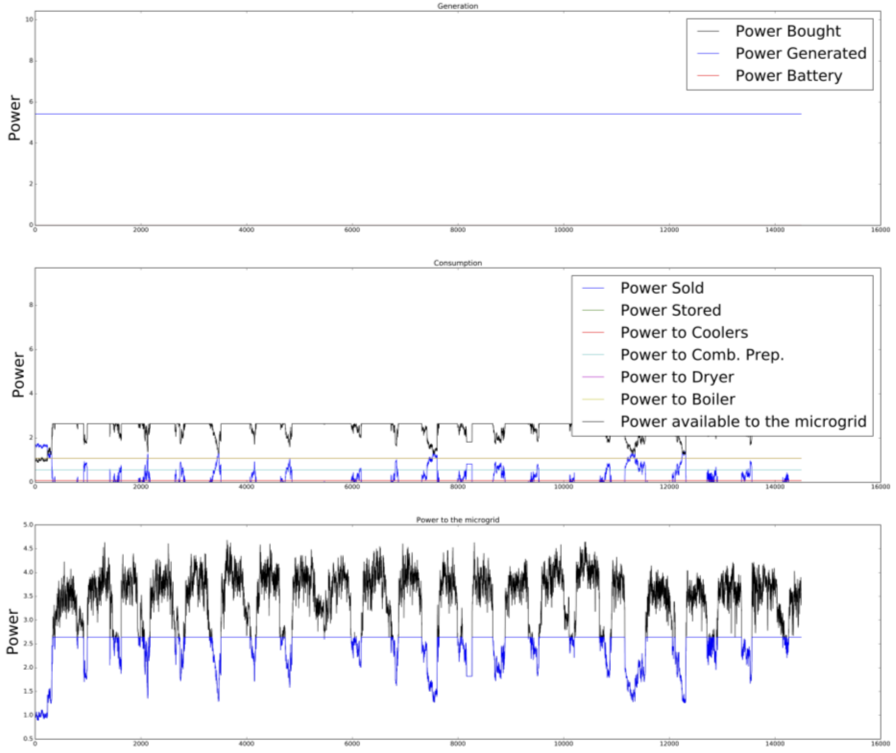


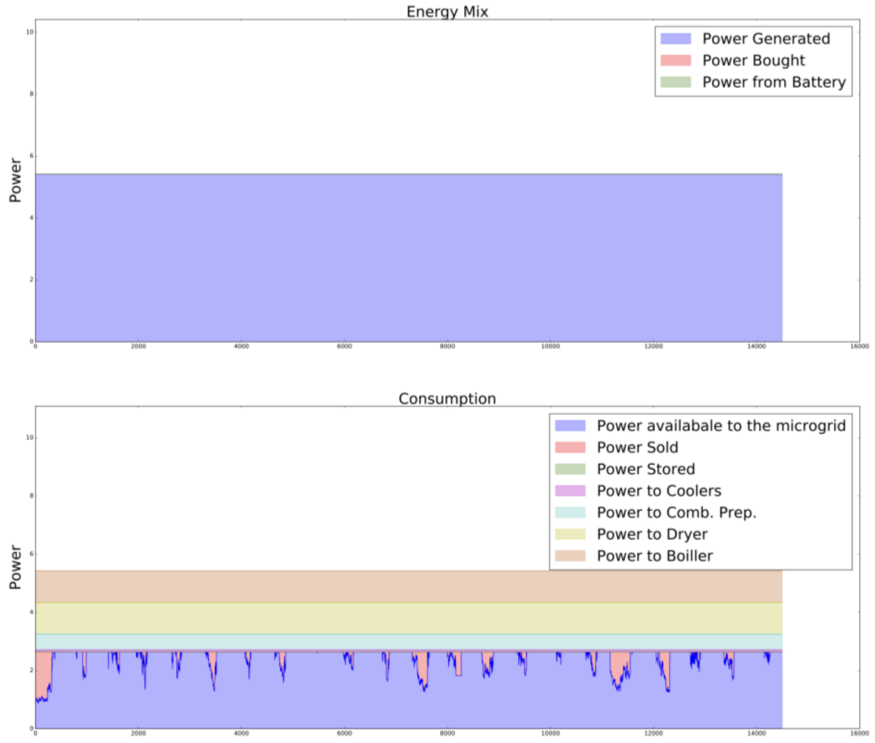
Dryer
Turbine
Boiler
Cooler
Combustible preparation
Dryer
Combustible preparation
Cooler
Turbine
5.9%
14.5%
0.3%
21.6%
57.6%
Boiler

Use case 2 results when industrial consumption taken into account

- Even if we consider 160 t/h in continuous flow for 16 hours a day
- That's more than 900,000 tons of material to be dried per year!
- The optimal size of the cogen is around 5 to 6 Mwe
  - (at 80 t/h, we fall to 3 Mwe)
- The demand of the other industrials on the site (4.5 Mwe in peak) is not covered, they are left with the variable...
- There is nevertheless, according to certain hypotheses, an interest in building a microgrid in this case
- But we did not take into account the additional costs, delays and worries (network layout, authorizations, etc.)
- The process should be made more flexible, or the demand of other industries.

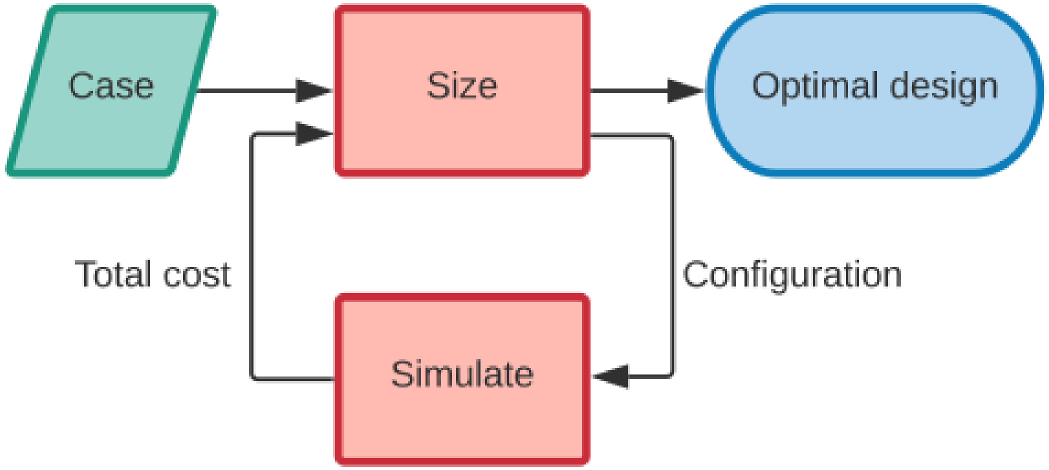
Unfavorable case, request from industrials, limit to 160 t/h



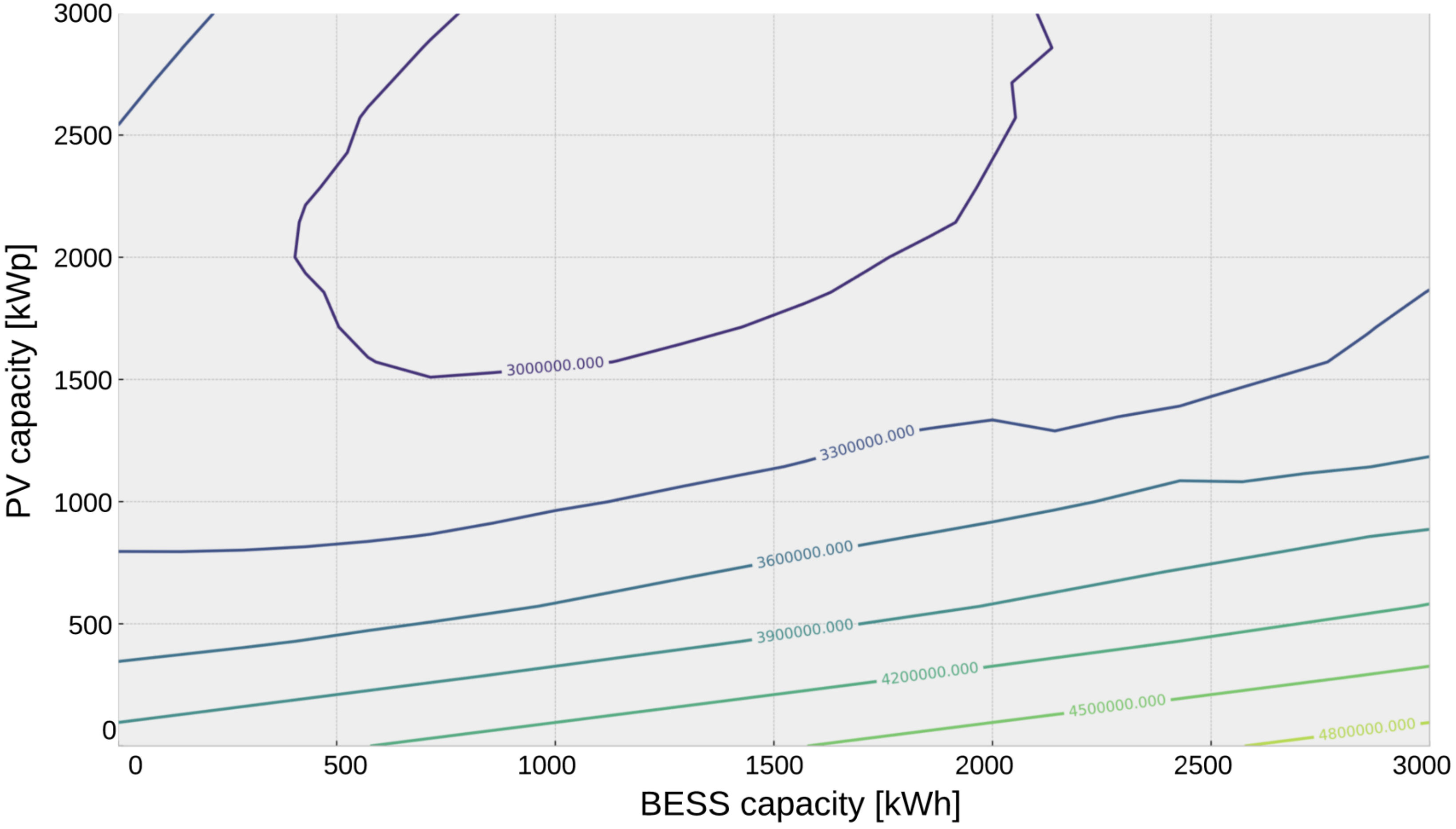


Simulation and optimization

- Dakir, S., & Cornélusse, B. (2020). **Combining optimization and simulation for microgrid sizing**. Paper submitted to PSCC 2020 XXI Power Systems Computation Conference, Porto, Portugal.



Use case 3 results



Difficulties

- Finding data
  - Since the microgrid does not exist yet, there is not necessarily past usage data easily available
  - Prices of equipment are not always easily available and can evolve significantly
- Foreseeing demand evolution
  - the creation of the microgrid, especially in remote villages, may attract new people, and may create new needs

Other use cases

- Cold storage
    - Dakir, S., Boukas, I., Lemort, V., & Cornélusse, B. (2019). **Sizing and Operation of an Isolated Microgrid with Cold Storage.** Powertech Milano 2019 Proceedings.
- Building thermal dynamics
    - Dakir, S., Boukas, I., Lemort, V., & Cornélusse, B. (2019). **Sizing and Operation of an Isolated Microgrid with Building Thermal Dynamics and Cold Storage**. EEEIC Genoa 2019
- Short-term & long-term storage
    - François-lavet, V., Gemine, Q., Ernst, D., & Fonteneau, R. (2016). **Towards the Minimization of the Levelized Energy Costs of Microgrids using both Long-term and Short-term Storage** Devices, 1–16.

References

- Kwasinski, A., Weaver, W., & Balog, R. S. (2016). Microgrids and other local area power and energy systems. Cambridge University Press. Chapter