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Predictive management of energy resources in a microgrid: a simulation case study

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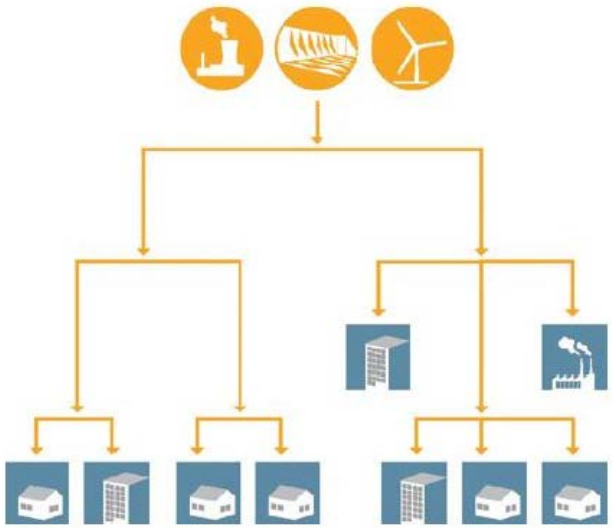
Summary

1. **Context and objectives**
2. **Energy resources management**
   - Evaluation criteria
   - Impact on the grid
   - Overview of the strategy
3. **Microgrid modeling**
   - Single-storey house
   - Energy production and storage systems
4. **Design and impact on the grid**
5. **Conclusion and outlook**

Context of the study

- Environmental issues and concerns are growing
- Fossil fuels are running out
- Decentralized energy production is developing
    - Intermittency in renewables
    - Production impacts on the grid operation and stability



Objectives

Develop a predictive strategy for managing energy resources in houses equipped with production (PV solar panels/windmills) and storage systems (batteries)

- Promote energy self-consumption
- Minimize the impact of energy production on the grid
- Manage electricity storage
- Control energy consumption/Load shifting

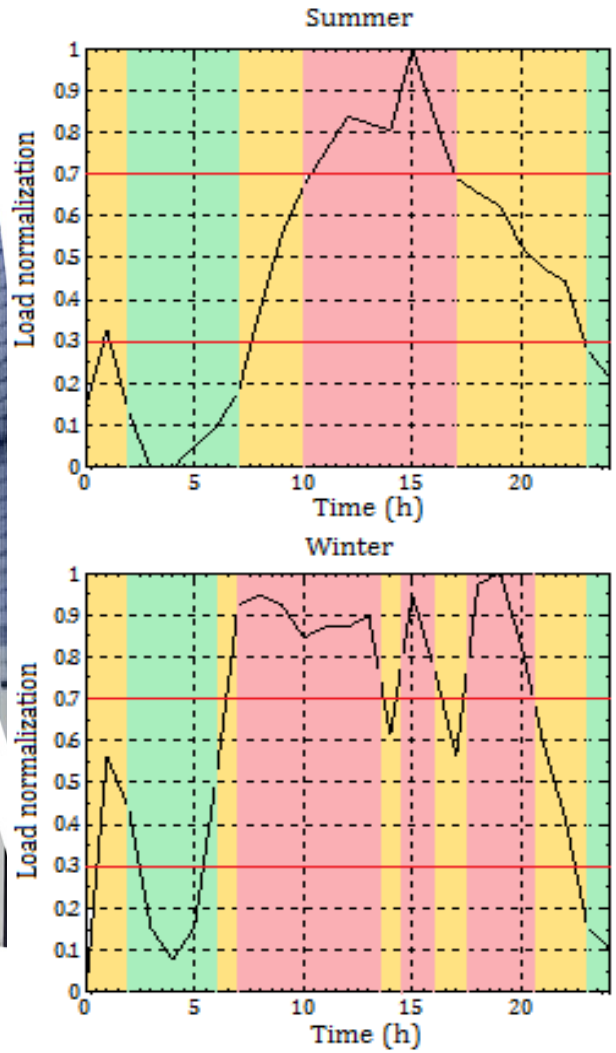
Energy criteria

- Renewable energy use: $J_{EnR} = \frac{\%_{EnR_C} \times \%_{SC}}{100}$
- Energy self-consumption: $\%_{SC} = 100 \times \frac{EnR_c}{EnR_p}$
- Renewable energy coverage rate: $\%_{EnR_c} = 100 \times \frac{EnR_c}{EnR_p + E_{EDF}}$
  - EnR_c is the amount of renewable energy consumed (kWh)
  - EnR_p is the amount of renewable energy produced (kWh)
  - E_{EDF} is the amount of energy extracted from the grid (kWh)
  - $\%_{EnR_c}$ is the ratio of the renewable energy produced and consumed in situ to the total energy consumed (%)
  - $\%_{SC}$ is the ratio of the renewable energy consumed in situ to the renewable energy produced (%)

Economic cost & dynamic pricing

- Economic cost: $J_{cost} = \sum_k E_{inj}(k) \cdot P_{En}(k) - E_{EDF}(k) \cdot P_{En}(k)$
- Dynamic pricing: $P_{En}(k) = \sum_{i,j} a_{ij} \times L_g^i(k) \times 10^{-3} \times T_{out}^j(k)$
  - E_{inj} is the amount of energy injected to the grid (kWh)
  - P_{En} is the energy price (€.kWh^{-1})
  - E_{EDF} is the amount of energy extracted from the electricity grid (kWh)
  - a_{ij} are the polynomial coefficients, $\forall i, j \in [\![1,5]\!]$
  - L_g is the electricity grid load (kW)
  - T_{out} is the outdoor temperature (°C)

Status of the grid and grid threshold



Energy demand

Periods	May, 1 to October, 31	November, 1 to April, 30
Peak periods	10:00 a.m. – 5:00 p.m.	7:00 a.m. - 1:30 p.m. 2:30 p.m. – 4:00 p.m. 5:30 p.m. - 8:30 p.m.
Part-peak periods	12:00 a.m. - 2:00 a.m. 7:00 a.m. - 10:00 a.m. 5:00 p.m. - 11:00 p.m.	12:00 a.m. - 2:00 a.m. 6:00 a.m. - 7:00 a.m. 1:30 p.m. - 2:30 p.m. 4:00 p.m. - 5:30 p.m. 8:30 p.m. - 11:00 p.m.
Off-peak periods	2:00 a.m. - 7:00 a.m. 11:00 p.m. - 12:00 a.m.	2:00 a.m. - 6:00 a.m. 11:00 p.m. - 12:00 a.m.

Grid threshold: 30% or 70%

Status of the grid:

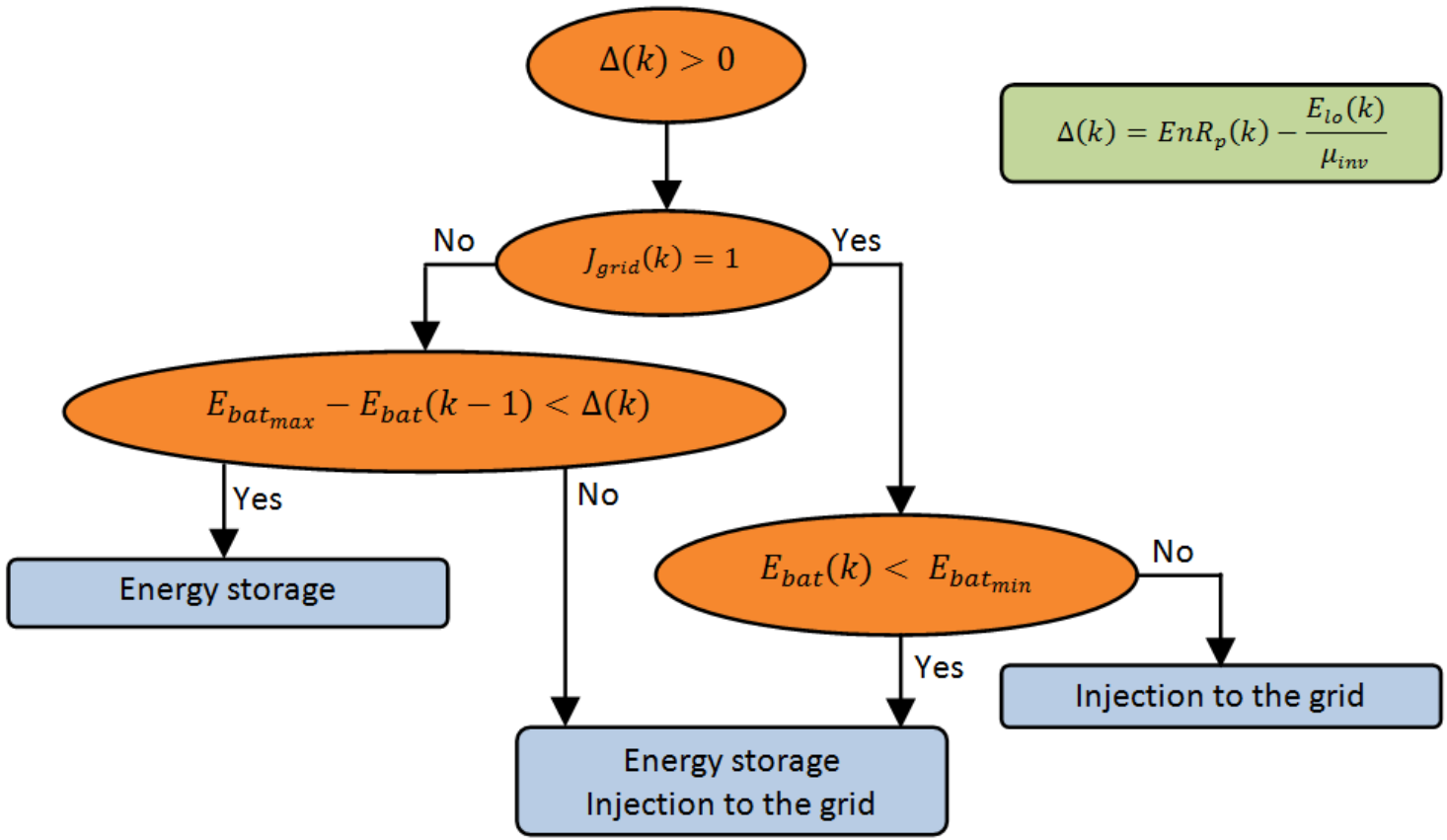
- Load > grid threshold : $J_{grid} = 1$
- Load < grid threshold : $J_{grid} = 0$

Impact on the grid

- Injection impact: $I_{inj} = \frac{1}{1000} \times \sum_k E_{inj}(k) \times \Delta E_{thres}(k)$
- Extraction impact: $I_{ext} = -\frac{1}{1000} \times \sum_k E_{EDF}(k) \times \Delta E_{thres}(k)$
- Overall impact: $I_{over} = I_{inj} + I_{ext}$
  - E_{inj} is the amount of energy injected to the grid (kWh)
  - E_{EDF} is the amount of energy extracted from the electricity grid (kWh)
  - ΔE_{thres} is the normalized deviation between the threshold and the status of the grid (-)

Non-predictive strategy (reference)

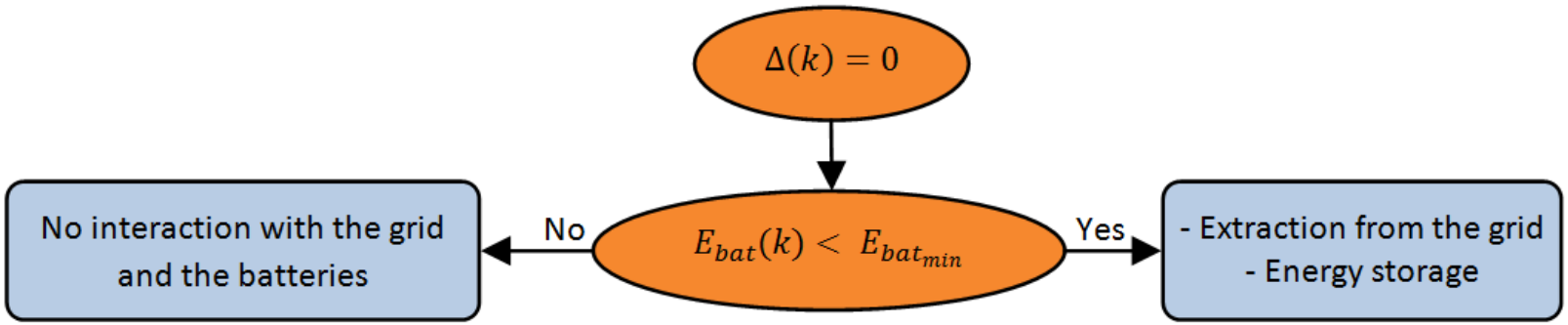
- Overproduction (1/3)



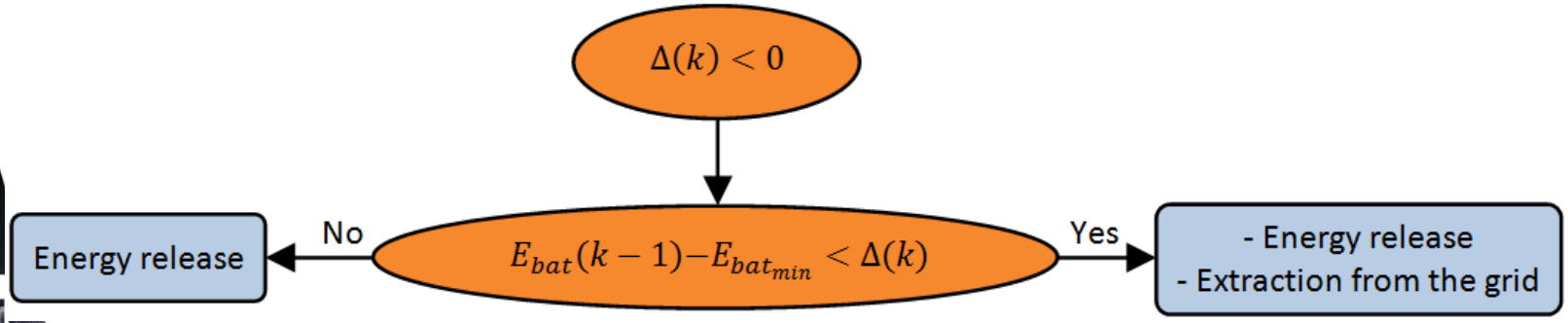
$$\Delta(k) = EnR_p(k) - \frac{E_{lo}(k)}{\mu_{inv}}$$

Non-predictive strategy (reference)

- Balance (2/3)

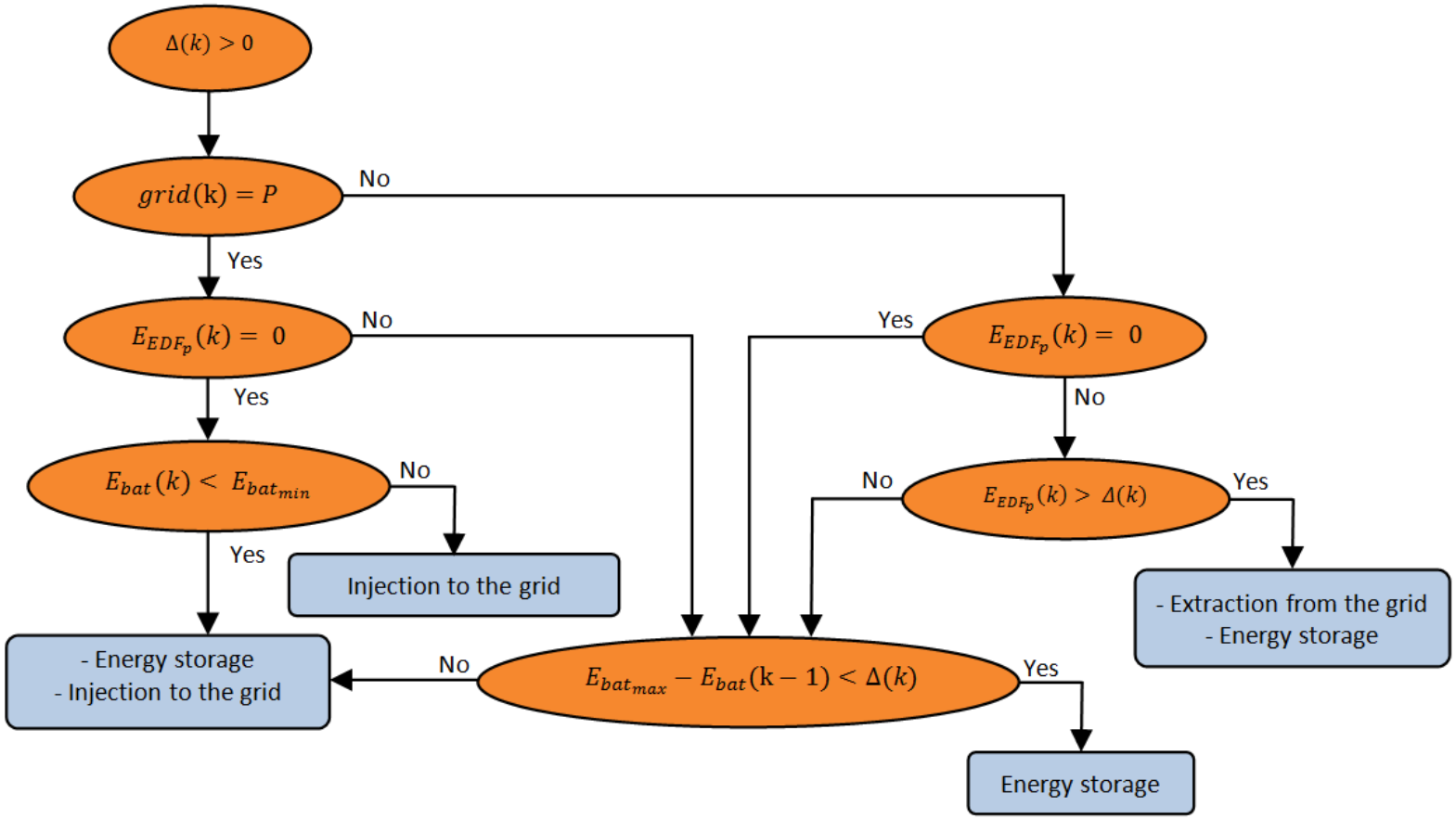


- Underproduction (3/3)



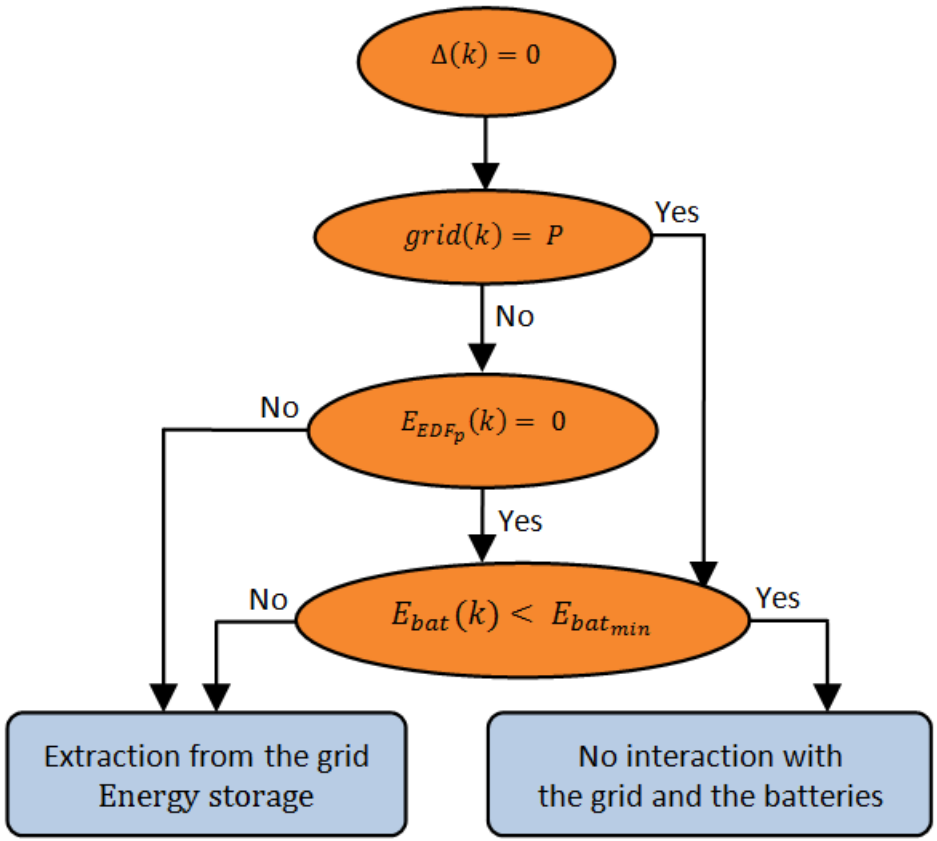
Predictive strategy

- Overproduction (1/3)



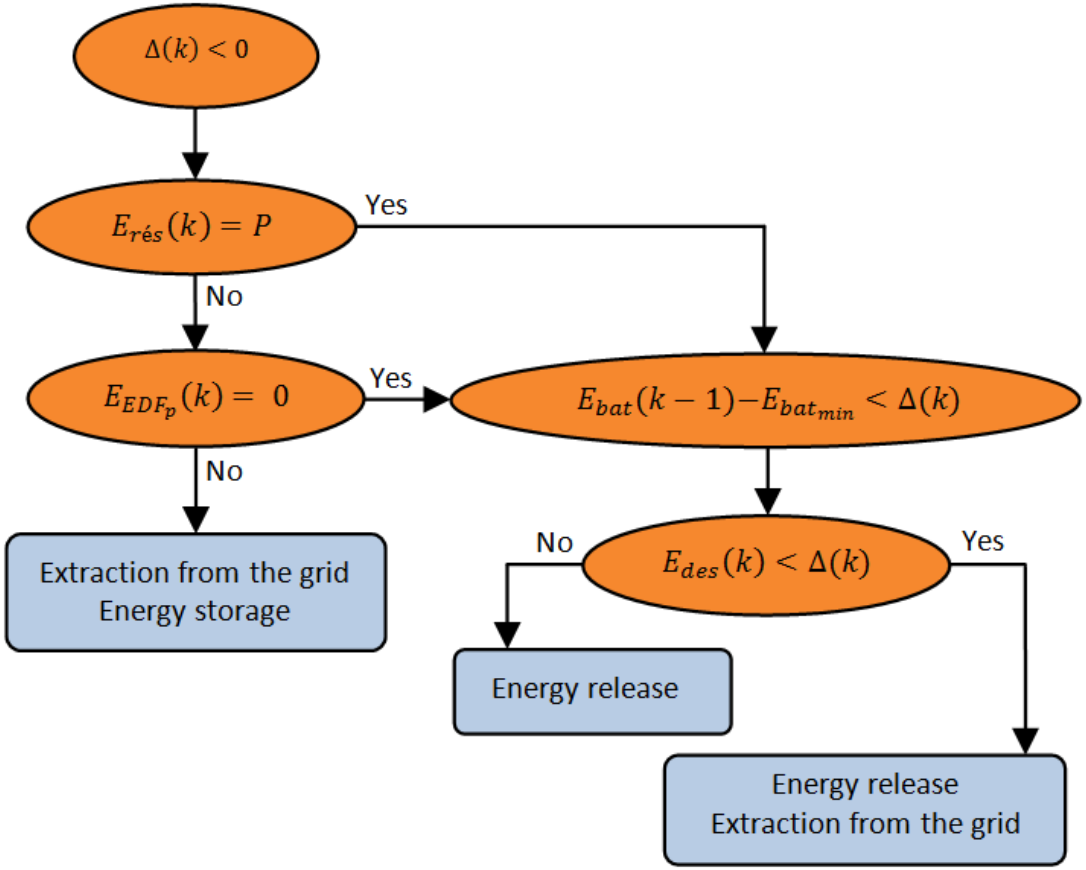
Predictive strategy

- Balance (2/3)



Predictive strategy

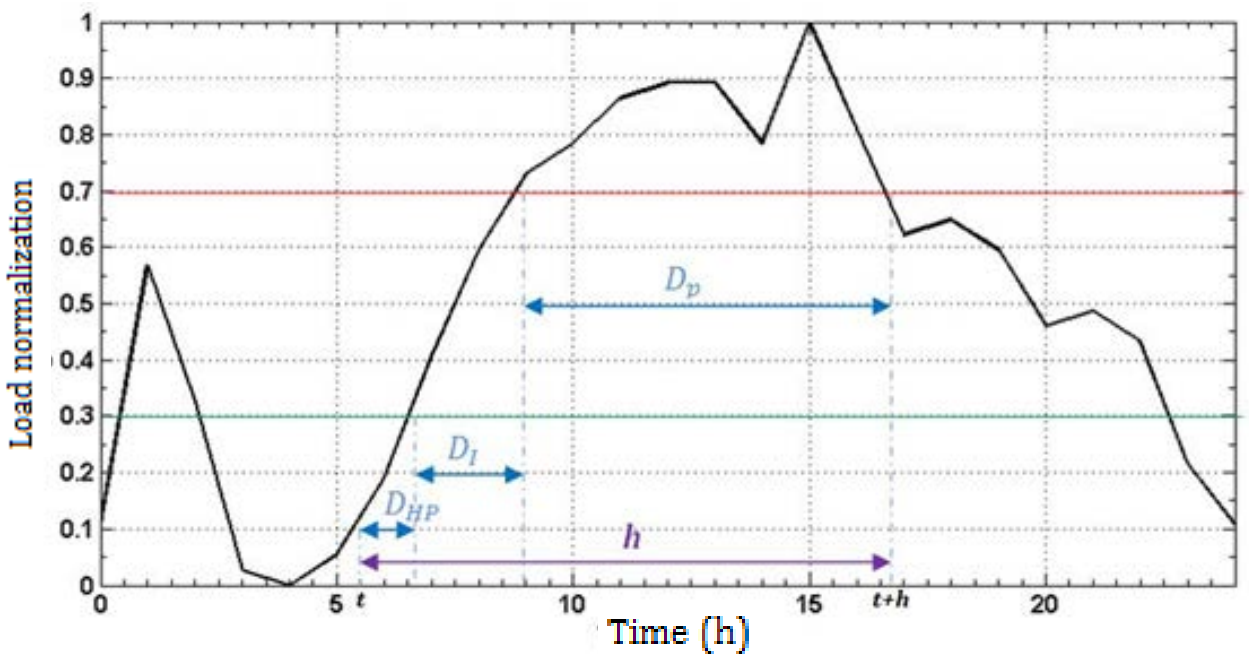
- Underproduction (3/3)



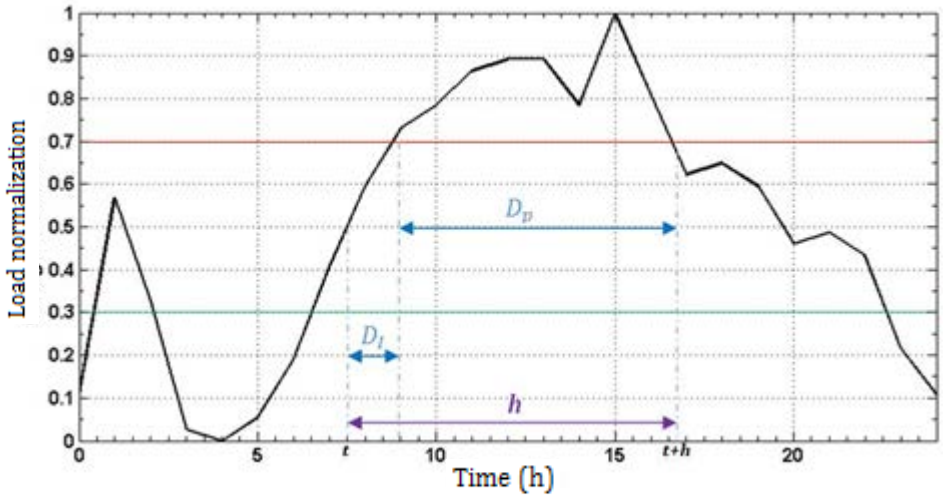
Prediction horizon

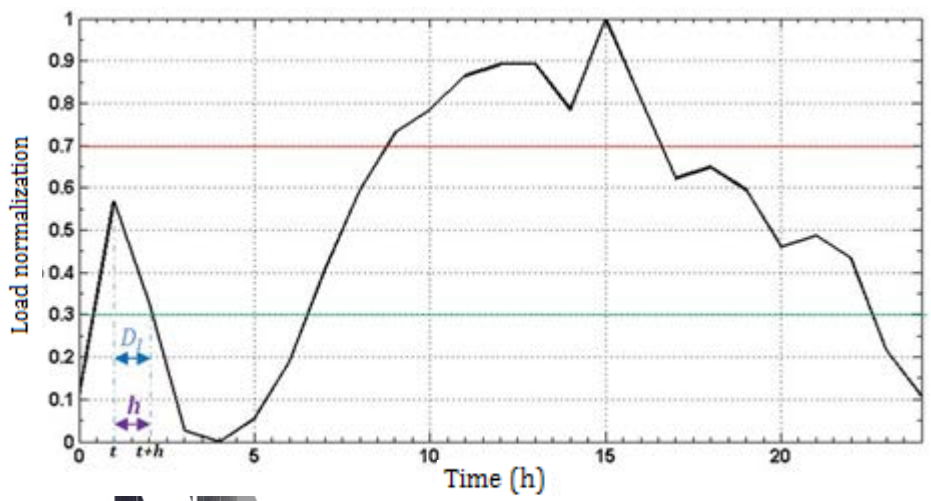
① Off-peak period:

- $h = D_{HP} + D_I + D_P$
- Threshold is 30%



Prediction horizon

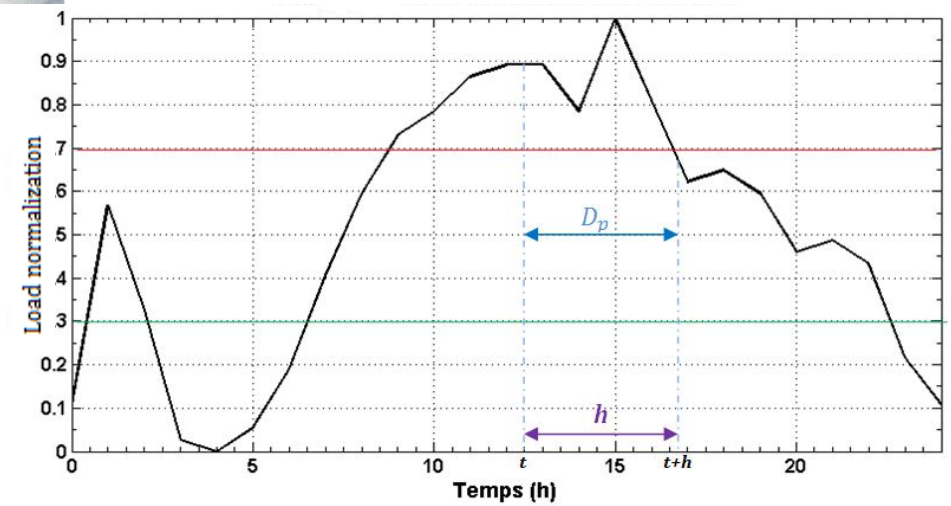


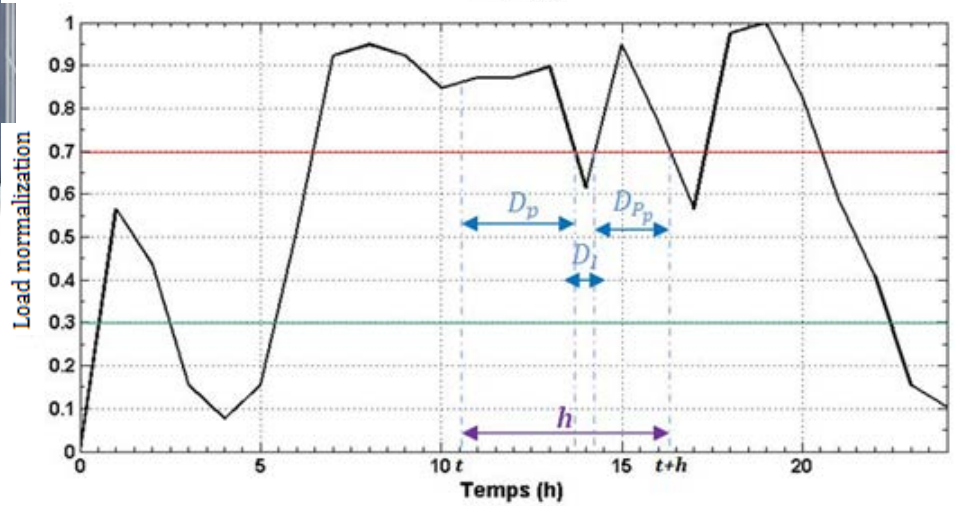


② Part-peak period:

- Followed by a peak period
  - $h = D_l + D_P$
  - Threshold is 70%
- Followed by an off-peak period
  - $h = D_l$
  - Threshold is 30%

Prediction horizon





③ Peak period:

- Followed by a part-peak period
  - $h = D_P$
  - Threshold is 70%
- Followed by a new peak period
  - $h = D_P + D_I + D_{Pp}$
  - Threshold is 70%

Prediction data

- Housing load:

$$L_h^{j+1}(k+i) = L_h^j(k+i) + \beta_h \times (T_{out}^{j+1}(k) - T_{out}^j(k))$$

- Electrical grid load:

$$L_g^{j+1}(k+i) = L_g^j(k+i) + \beta_g \times (T_{out}^{j+1}(k) - T_{out}^j(k))$$

L_h^{j+1}	:	Housing load prediction (kWh)
L_h^j	:	Housing load of previous day (kWh)
L_g^{j+1}	:	Grid load prediction (kWh)
L_g^j	:	Grid load of previous day (kWh)
T_{out}	:	Outside temperature (°C)
j	:	Index day of the year
i	:	Time index for predicting with i=k:k+h
k	:	Time index
β	:	Parameter to optimize ($\beta_h = 0{,}1$ et $\beta_g = 0{,}001$)

Prediction data

- PV production:

$$EnR_{PV}^{j+1}(k+i) = EnR_{PV}^{j}(k+i) + \beta_{\mathrm{PV}} \times (I_r^{j+1}(k) - I_r^{j}(k))$$

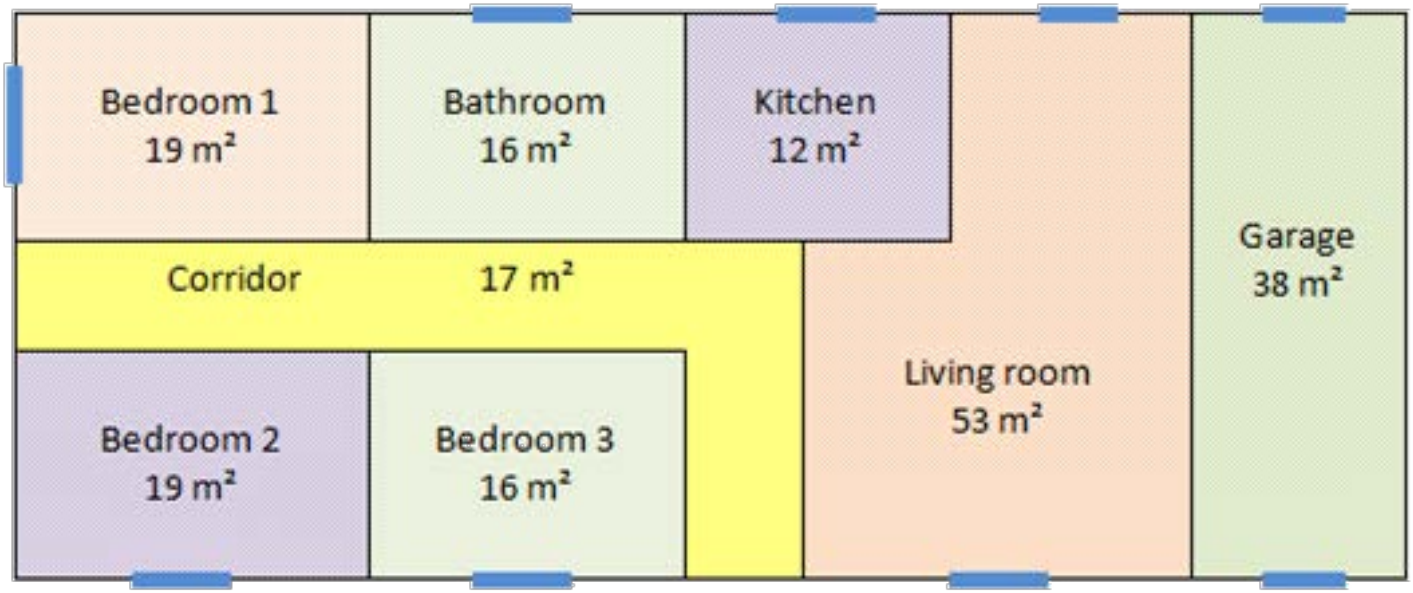
- Vertical-axis windmill production:

$$EnR_{wind}^{j+1}(k+i) = EnR_{\mathrm{wind}}^{j}(k+i) + \beta_{\mathrm{wind}} \times (V_{\mathrm{wind}}^{j+1}(k) - V_{\mathrm{wind}}^{j}(k))$$

EnR_{PV}^{j+1}	:	PV production prediction (kWh)
EnR_{PV}^{j}	:	PV production of previous day (kWh)
EnR_{wind}^{j+1}	:	Windmill production prediction (kWh)
EnR_{wind}^{j}	:	Windmill production of previous day (kWh)
I_r	:	Solar irradiation (kWh.m^{-2})
V_{wind}	:	Wind speed (m.s^{-1})
j	:	Index day of the year
i	:	Time index for predicting with i=k:k+h
k	:	Time index
β	:	Parameter to optimize ($\beta_{PV} = 0{,}001$ et $\beta_{wind} = 1{,}1$)

TRNSYS thermal model of an individual house

Case study: 150 m² single-storey house located in Perpignan (south of France), facing south and inhabited by four persons (two adults and two children)



TRNSYS thermal model of an individual house

Characteristics of the materials used in the considered single-storey house:

Element	Material	Thickness [m]	U [W.m^{-2}.K^{-1}]	U_{RT2005} [W.m^{-2}.K^{-1}]
External wall	BA13	0.013	0.602	0.45
	Rockwool	0.06		
	Cinderblock	0.2		
	Surface coating	0.02		
Internal wall	BA13	0.013	0.845	/
	Glass wool	0.04		
	BA13	0.013		
Floor	Tiles	0.022	0.415	0.4
	Mortar	0.05		
	Heavy concrete	0.16		
	Expanded polystyrene	0.08		
Ceiling	BA13	0.013	0.196	0.34
	Glass wool	0.1		
	Air knife	0.5		
	Terracotta	0.01		
Garage ceiling	BA13	0.013	2.37	0.34
	Terracotta	0.2		
Window	Double glazed	0.2	1.43	2.6

Modeling of lifestyle and habits

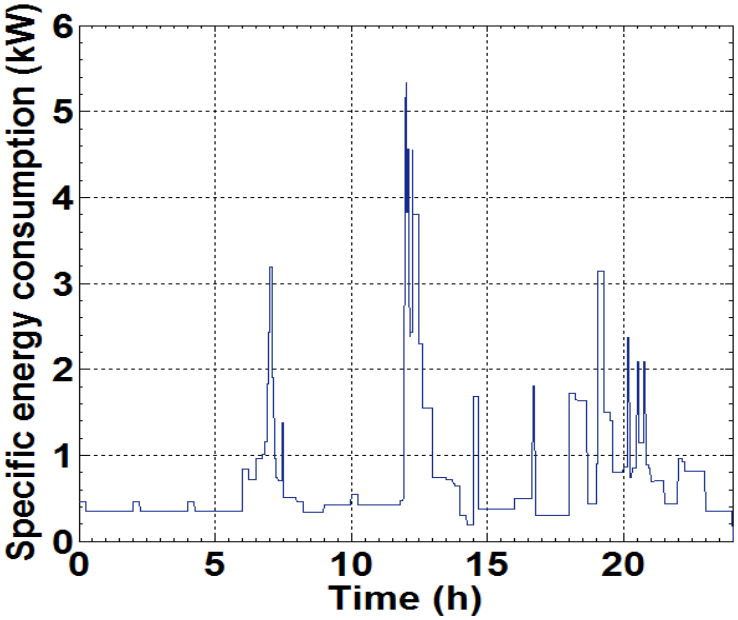
Conventional occupation scenario set by RT 2005

Week occupancy	Weekend occupancy
0h-10h ; 18h-24h	0h-24h

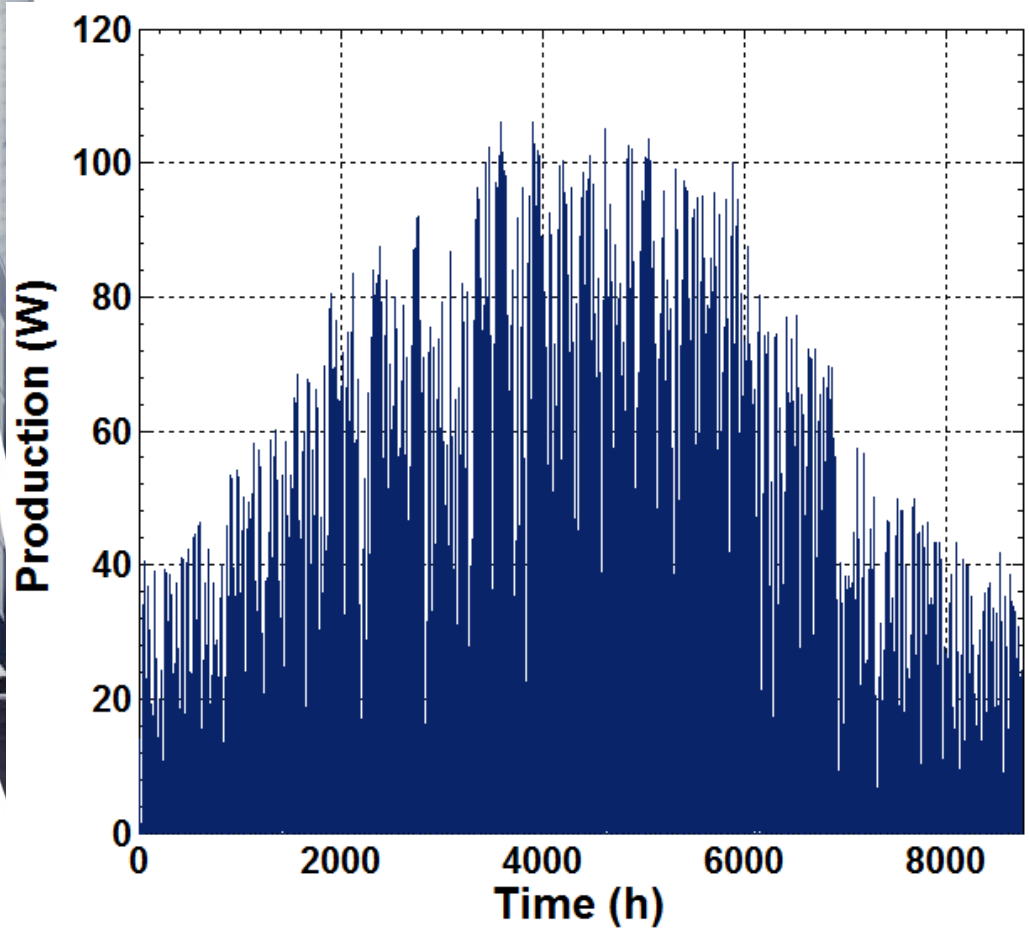
Conventional French RT 2005 temperature set-points

Set point	Occupancy periods	Non occupancy periods
Heating	19°C	16°C
Air conditioning	28°C	30°C

Behaviour scenario



Production and storage systems modeling (energy mix)

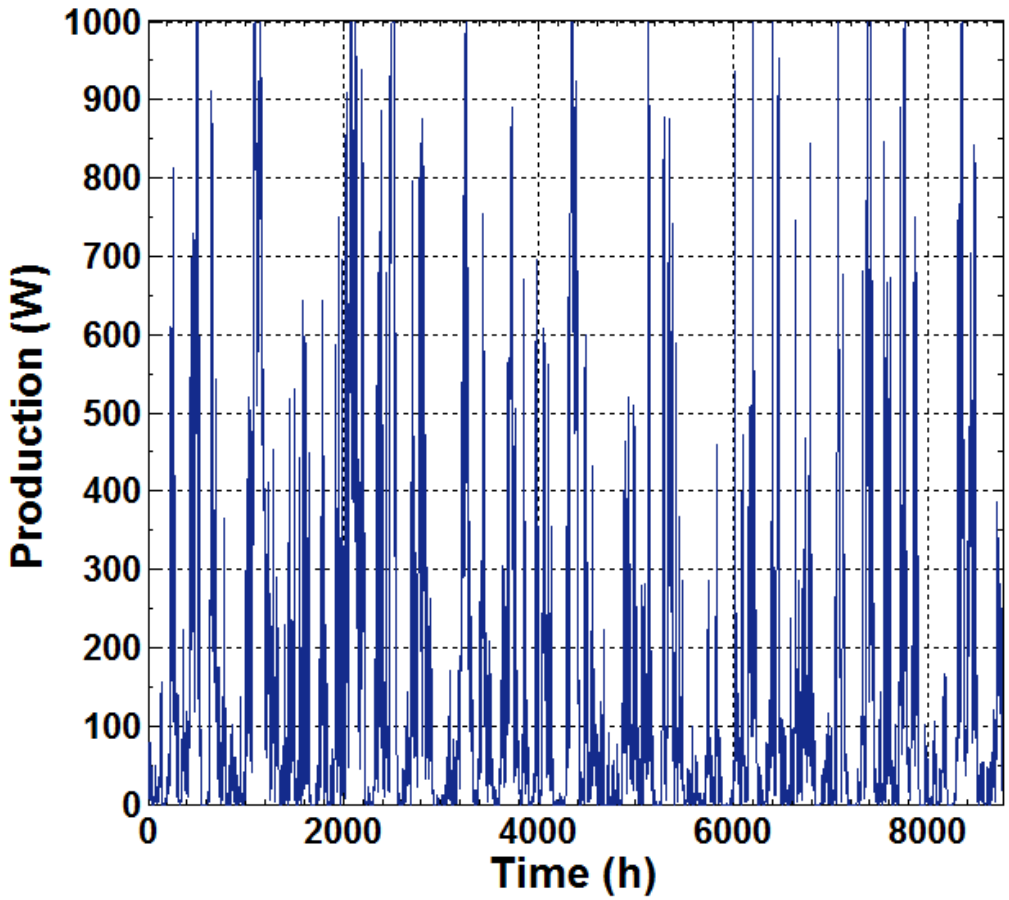


Photovoltaic array
TRNSYS model 194

- Based on the calculation method presented by DeSoto[1] and defined with various semi-empirical equations
- Determines the current and power of a photovoltaic array at a specific voltage

[1] DeSoto W., Klein S.A., Beckman W.A., 2006. Improvement and validation of a model for photovoltaic array performance, Solar Energy, vol. 80, pp. 78-88.

Production and storage systems modeling (energy mix)



Vertical-axis windmill

TRNSYS model 90

- Based on the work of Quilan[1]
- Calculates the power output of energy conversion systems based on a power versus wind speed characteristics

[1] Quilan P.J., 2000. A time-series wind turbine array simulator. In Proceeding of ASES Conference SOLAR 2000, Madiso, USA.

Production and storage systems modeling (energy mix)

Description of the functioning of the batteries:

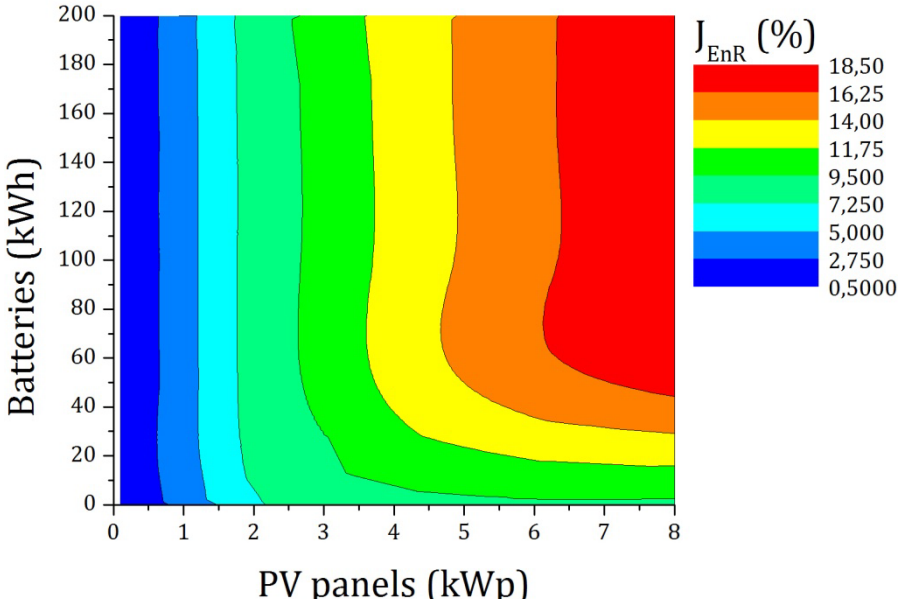
- Charging mode: $E_{bat}(t) = (1-\tau)\cdot E_{bat}(t-1) + \left(E_{EnR}(t) - \frac{E_{ch}(t)}{\eta_{inv}}\right)\cdot \eta_{bat}$
- Discharging mode: $E_{bat}(t) = (1-\tau)\cdot E_{bat}(t-1) + \left(\frac{E_{ch}(t)}{\eta_{inv}} - E_{EnR}(t)\right)$

Constraints: $E_{bat_{min}} = (1-DOD)\times E_{bat_{max}}$ and $E_{bat_{max}} = C_n$

η_{inv} : Inverter performance
η_{bat} : Charge performance
E_{bat} : Energy stored (kWh)
E_{ch} : Energy required (kWh)
E_{EnR} : Energy produced by the local production systems (kWh)
τ : Hourly self-discharge rate
DOD : Depth Of Discharge
C_n : Nominal capacity (kWh)

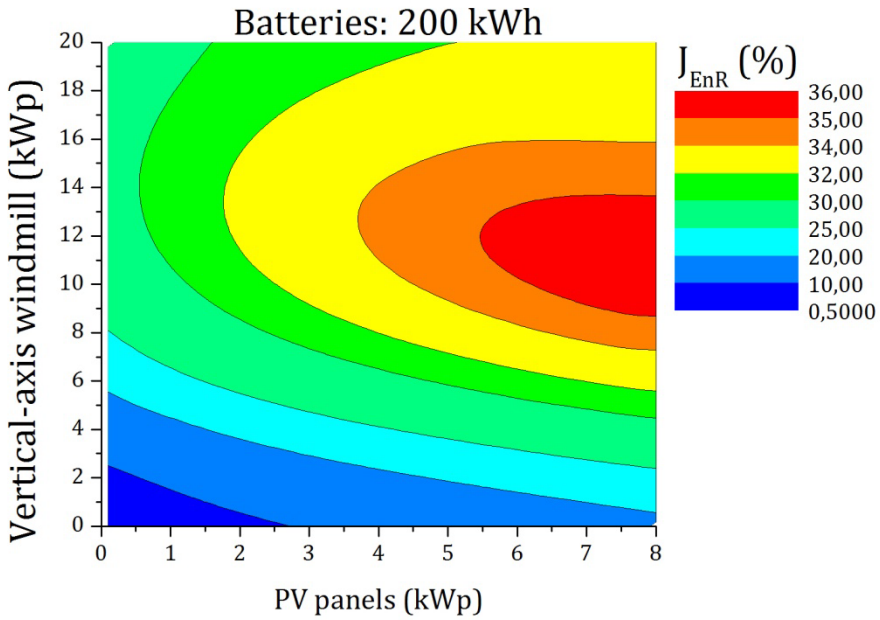
Design of energy production and storage systems (predictive)

With PV panels and batteries



PV (8 kWc) – Batteries (130 kWh)

With PV panels, a vertical-axis windmill and batteries



PV (7.6 kWc) – Windmill (11 kWc) – Batteries (200 kWh)

Design of energy production and storage systems (predictive)

With PV panels and batteries

System / Criterion	Predictive	No predictive without storage	No predictive with storage 70% threshold	No predictive with storage 30% threshold
PV panels (kWp)	8	8	8	8
Batteries (kWh)	130	-	130	130
EnR_c (kWh)	8011	5632	7988	5736
EnR_{inj} (kWh)	3404	6201	3428	6079
E_{EDF} (kWh)	21367	23743	21383	23647
E_{st} (kWh)	17882	6	2362	111
$\%_{SC}$ (%)	67.70	47.60	67.50	48.47
$\%_{EnR_c}$ (%)	27.27	19.17	27.19	19.53
J_{EnR} (%)	18.46	9.13	18.36	9.46
J_{cost} (€)	-1035.34	-1011.08	-1034.89	-1013

Design of energy production and storage systems (predictive)

With PV panels and batteries

System / Criterion			Predictive	No predictive without storage	No predictive with storage 70% threshold	No predictive with storage 30% threshold
PV panels (kWp)			8	8	8	8
Batteries (kWh)			130	-	130	130
Threshold	70%	I_{inj}	1316	778	1318	859
		I_{sout}	12800	5233	6390	6790
		I_g	14116	6011	7709	7649
	30%	I_{inj}	2509	3518	2524	3580
		I_{sout}	4636	-3119	-1415	-2172
		I_g	7145	399	1108	1407

Design of energy production and storage systems (predictive)

With PV panels, a vertical-axis windmill and batteries

System / Criterion	Predictive	No predictive without storage	No predictive with storage 70% threshold	No predictive with storage 30% threshold
PV panels (kWp)	7.6	7.6	7.6	7.6
Vertical axis windmill (kWp)	11	11	11	11
Batteries (kWh)	200	-	200	200
EnR_c (kWh)	16388	12057	16382	13244
EnR_{inj} (kWh)	8589	13681	8590	12284
E_{EDF} (kWh)	13001	17318	12998	16141
E_{st} (kWh)	14423	-	4330	1195
$\%_{SC}$ (%)	63.67	46.85	63.65	51.46
$\%_{EnR_c}$ (%)	55.79	41.05	55.77	45.09
J_{EnR} (%)	35.52	19.23	35.50	23.20
J_{cost} (€)	-220.98	-209.59	-254.03	-222.27

Design of energy production and storage systems (predictive)

With PV panels, a vertical-axis windmill and batteries

System / Criterion			Predictive	No predictive without storage	No predictive with storage 70% threshold	No predictive with storage 30% threshold
PV panels (kWp)			7.6	7.6	7.6	7.6
Vertical axis windmill (kWp)			11	11	11	11
Batteries (kWh)			200	-	200	200
Threshold	70%	I_{inj}	4550	-145	1327	1001
		I_{sout}	2713	4762	3525	4368
		I_g	7453	4616	4852	5369
	30%	I_{inj}	1316	5762	4561	6859
		I_{sout}	7625	-1812	-1219	-1734
		I_g	8940	3950	3342	4843

Conclusion

- Several configurations promoting energy self-consumption are highlighted
- Impact of local production on the grid is minimized
- Better match between decentralized production, energy needs and injection to the grid