IMPROVEMENT energy management system for multi-energy microgrids

March 7, 2023, Seville, Spain

Romain Mannini
Julien Eynard
Stéphane Grieu

Summary

Components

- solar collectors (SC)
- hot water tank (HWT)
- thermal energy storage (TES)
- heat pump
- fan coil units (FCUs)
- 4 rooms
- PV panels
- bank of batteries
- loads

Objectives

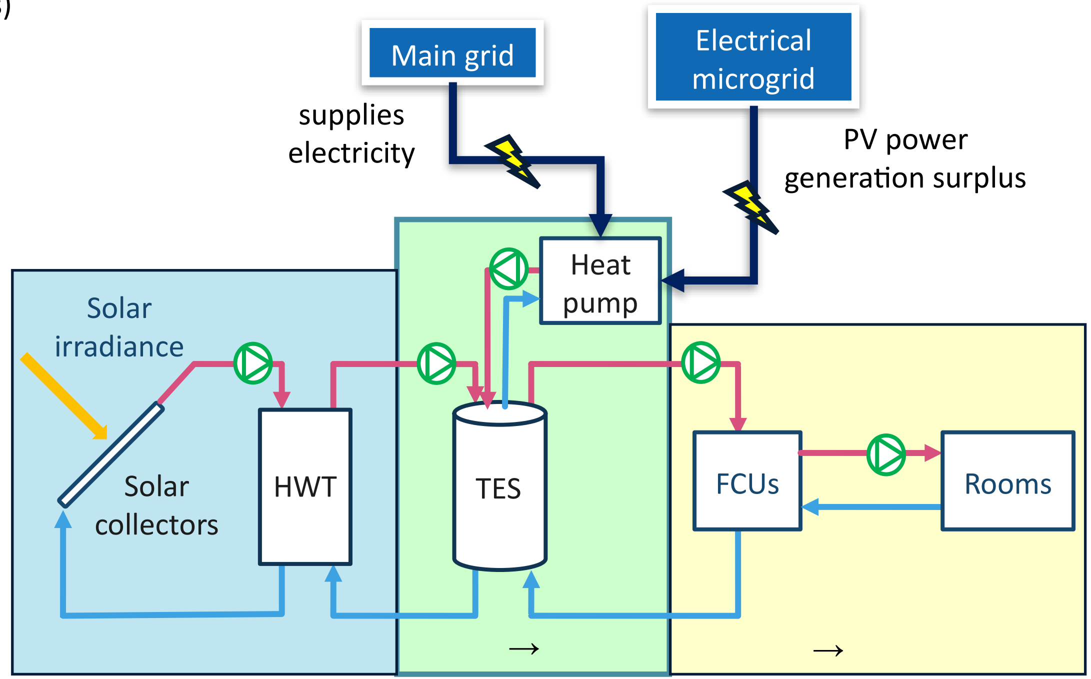
- manage thermal energy
- satisfy thermal comfort constraints
- evaluate the islanding ability of the multi-energy microgrid

PID/rule-based (PID/RB) EMS

- SC control:
- HP control:
- FCU control:

MPC-based (/) EMS

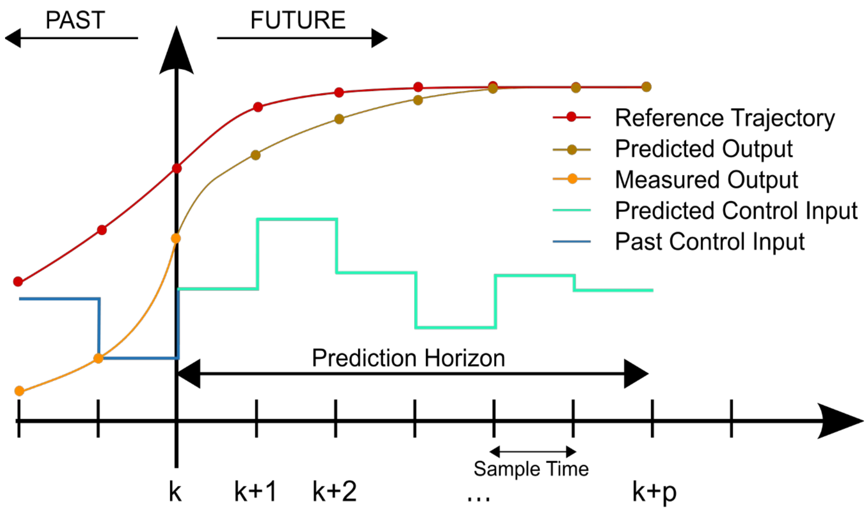
- Optimization-free MPC for the HP:
- Optimization-free MPC for the FCUs:
- Optimization-based MPC for the HP:
- Optimization-based MPC for the FCUs:



LNEG thermal microgrid: MPC control

Considerations

- MPC allows a reference trajectory to be followed
- An MPC controller determines from **future states** of the system the **best control inputs** along the **prediction horizon**
- An MPC controller applies to the system the best control inputs for the **current states based on predictions**
- MPC is useful in case of uncertainties (PV power generation intermittency, energy price fluctuations…)



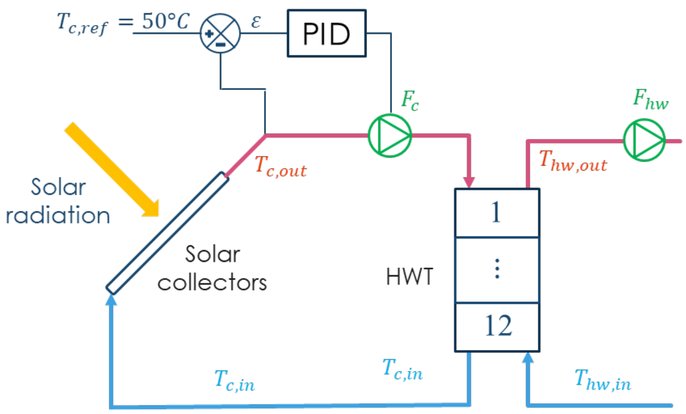
MPC principle

https://en.wikipedia.org/wiki/Model_predictive_control

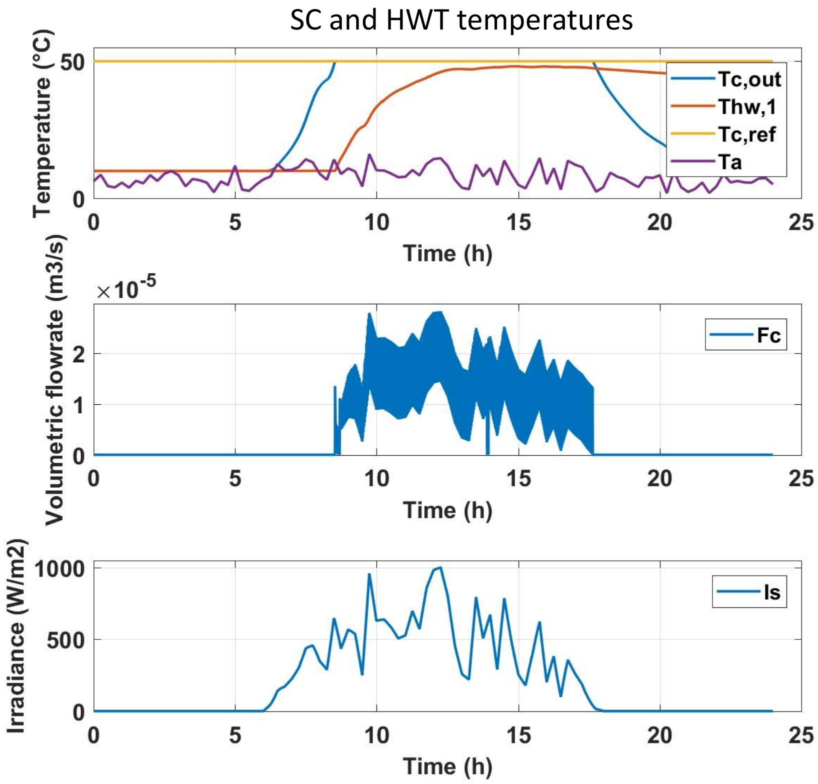
Research question

→ will **EMS** provide better results than **PID-RB EMS** regarding **thermal energy management and thermal comfort constraints satisfaction in grid-connected mode and islanded mode**?

Solar collectors model, proposed by Buzás *et al.* [1] (to benefit from a simple model; complex models impact significantly computation time)
Heat balance of a solar collector:



: ambient temperature (10°C)
: irradiance ()
: volumetric flow rate of the SC fluid ()



[1] Buzás, J., I. Farkas, A. Biró, and R. Németh. 1998. 'Modelling and Simulation Aspects of a Solar Hot Water System'. *Mathematics and Computers in Simulation* 48 (1): 33–46. https://doi.org/10.1016/S0378-4754(98)00153-0.

Stratified tank model, adapted from Rahman *et al.* [2] and Nash *et al.* [3]

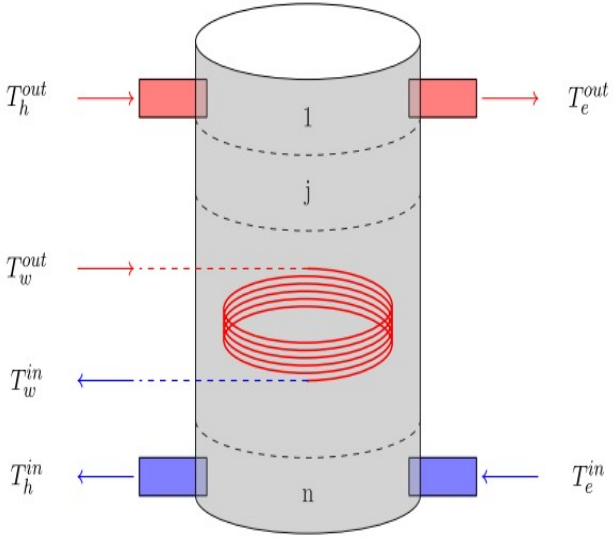
Heat balance for one layer inside the tank (12 layers):

with

with and

Heat balance for one layer inside the coil of the heat exchanger (5 layers):

with



TES scheme

[2] Rahman, Aowabin, Amanda Smith, and Nelson Fumo. 2016. 'Performance Modeling and Parametric Study of a Stratified Water Thermal Storage Tank'. *Applied Thermal Engineering* 100. https://doi.org/10.1016/j.applthermaleng.2016.01.163.

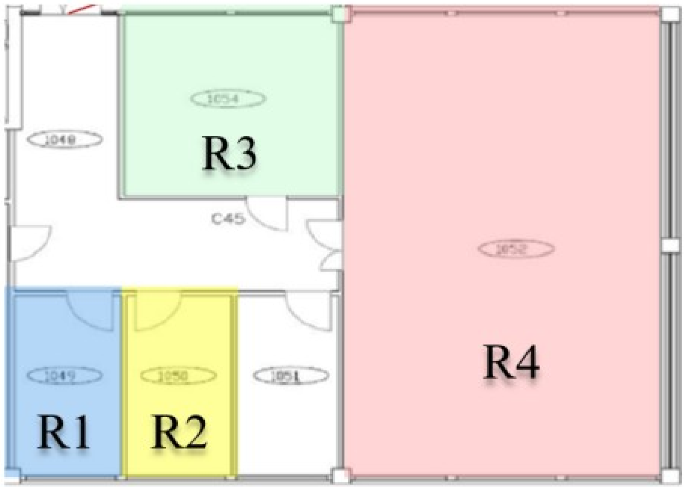
[3] A. L. Nash, A. Badithela, and N. Jain, 'Dynamic modeling of a sensible thermal energy storage tank with an immersed coil heat exchanger under three operation modes', *Applied Energy*, vol. 195, pp. 877–889, Jun. 2017, doi: 10.1016/j.apenergy.2017.03.092.

FCU model (Peter *et al.* [4])
Heat balance for the tube-side (co-current) of the FCU:

Heat balance for the shell-side (co-current) of the FCU:

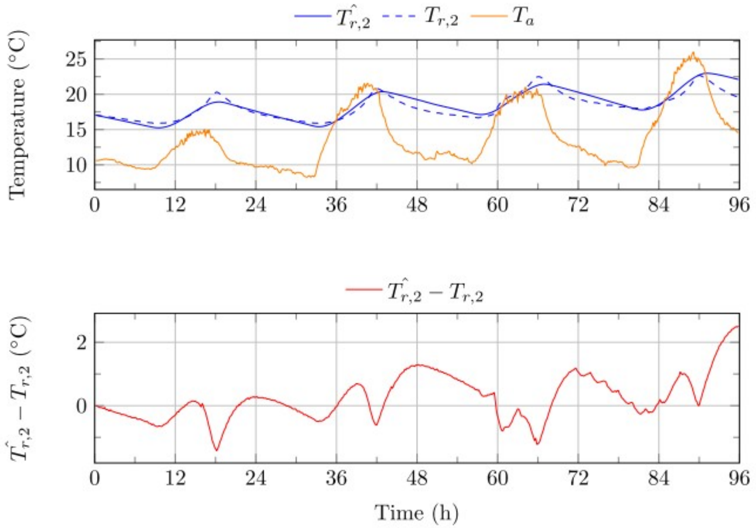
RC thermal model of room z (Darure *et al.* [5], Stamp *et al.* [6], Garnier *et al.* [7])
Heat balance of room z:

with

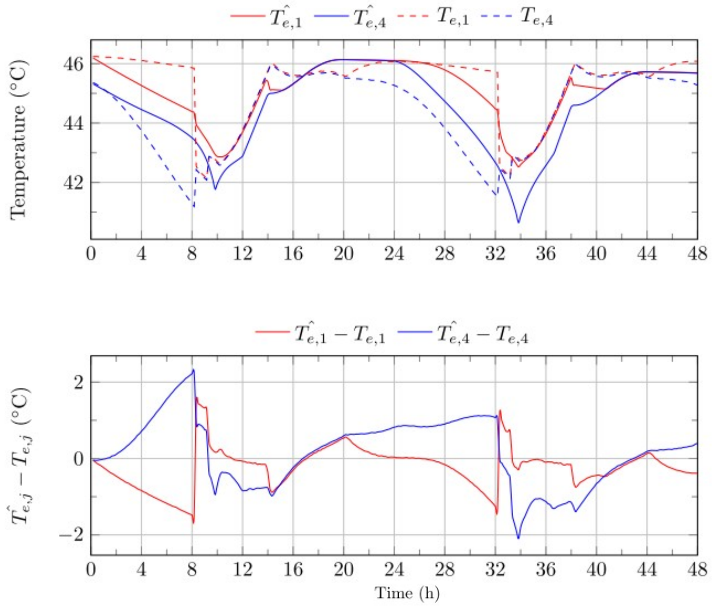


The LNEG building

[4] Peter, Woolf. 2020. 'Book: Chemical Process Dynamics and Controls (Woolf)'. Engineering LibreTexts. 19 May 2020. https://eng.libretexts.org/Bookshelves/Industrial_and_Systems_Engineering/Book%3A_Chemical_Process_Dynamics_and_Controls_(Woolf).
[5] Darure, Tejaswinee. 2017. 'Contribution to Energy Optimization for Large-Scale Buildings: An Integrated Approach of Diagnosis and Economic Control with Moving Horizon'. Phdthesis, Université de Lorraine. https://tel.archives-ouvertes.fr/tel-01647139.
[6] S. Stamp, H. Altamirano-Medina, and R. Lowe, 'Measuring and accounting for solar gains in steady state whole building heat loss measurements', *Energy and Buildings*, vol. 153, pp. 168–178, Oct. 2017, doi: 10.1016/j.enbuild.2017.06.063.
[7] A. Garnier, J. Eynard, M. Caussanel, and S. Grieu, 'Low computational cost technique for predictive management of thermal comfort in non-residential buildings', *Journal of Process Control*, vol. 24, no. 6, pp. 750–762, Jun. 2014.



R2 thermal zone model validation, from February 19 to February 22



TES model validation, from May 11 to May 12

Observation

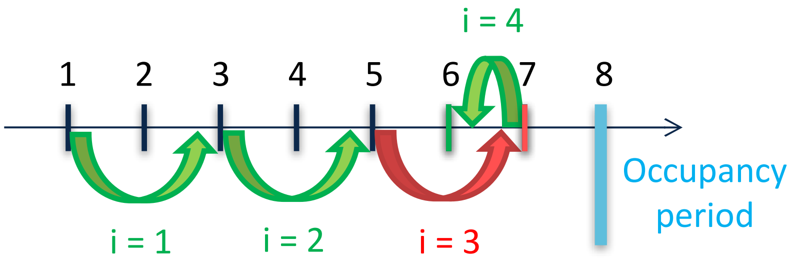
- The error between the model and the data is below 2.2°C for both the TES and the thermal zones

II/ Users' thermal comfort management
1) Optimization-free MPC-based EMS (EMS)

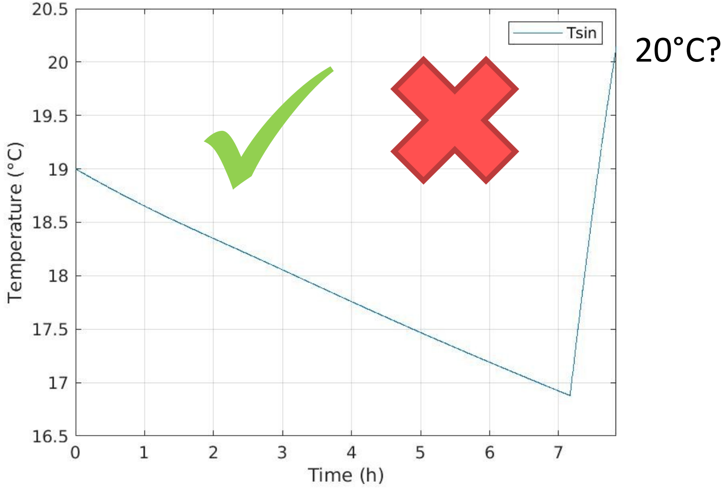
Objectives
- reduce energy consumption
- satisfy thermal comfort constraints (20°C - 22°C)

Strategies
- **turn on** the FCU before an occupation period at the **optimal time**
- **turn off** the FCU before the end of the occupation period at the **optimal time**

Optimization-free method
- check for the next time steps to turn **on** or turn **off the FCU** according to the next occupancy or non-occupancy period
- select which time step is the optimal one to turn **on** or turn **off the FCU**



Optimal time to turn the FCU on (example)



Air temperature () in the room 4 with different tests

II/ Users’ thermal comfort management
2) Optimization-based MPC-based EMS (EMS)

Objectives

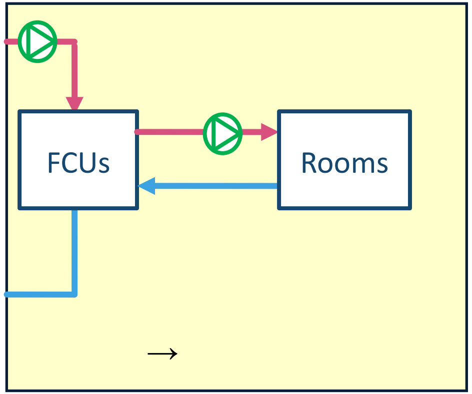
- reduce energy consumption
- satisfy thermal comfort constraints

Optimization problem

with the optimal time step to turn on or turn off the FCU of room

for thermal comfort, air temperature in the room has to be between 20°C and 22°C:

if or
then



LNEG thermal microgrid: MPC control

: energy supplied to the room by the FCU (kWh)

: penalty for not respecting thermal comfort in the room

: coefficients

: objective function in the room

: minimal temperature to respect (°C)

: maximal temperature to respect (°C)

: optimal time step to turn off/on the FCU in the room

: actual time step

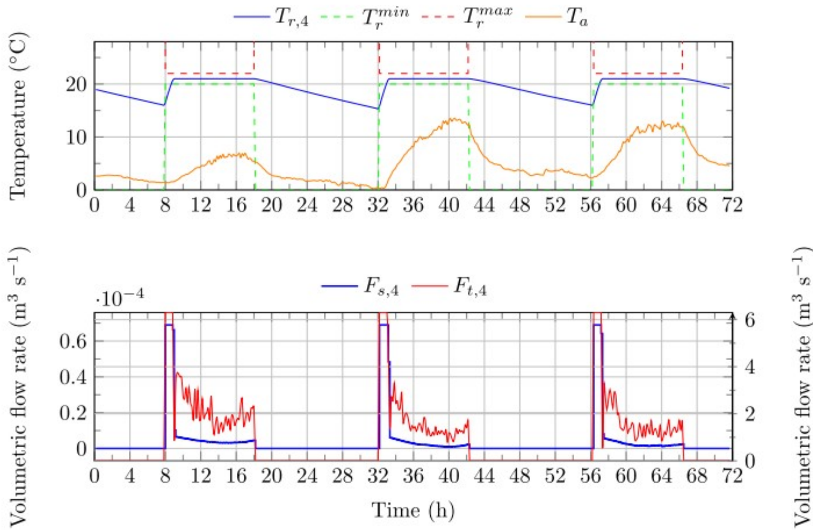
: prediction step

: index of the room

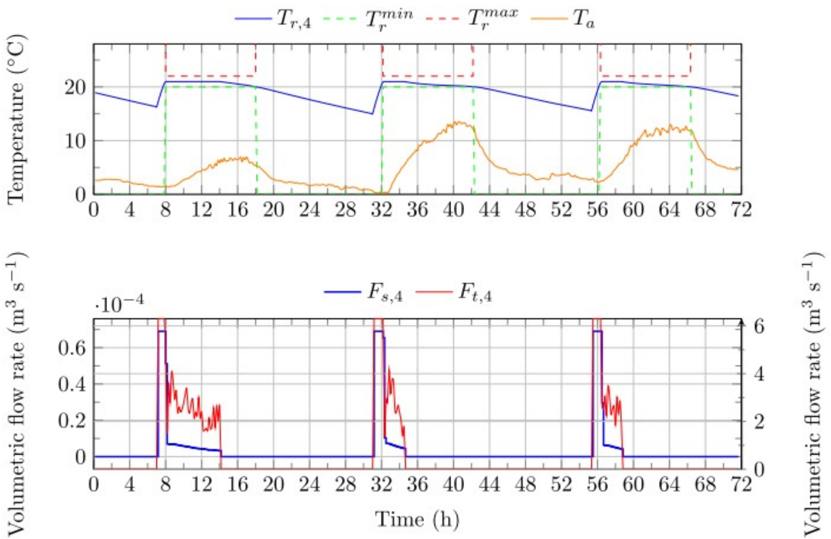
II/ Users' thermal comfort management

3) Comparison between PID/RB EMS and MPC-based EMS

PID/RB EMS



EMS



Observations (3 winter days created in simulation from real data)

- PID/RB EMS let FCU of room on during the 3 days
- EMS anticipates optimal instants to turn on or to turn off the FCU of room

II/ Users’ thermal comfort management

3) Comparison between PID/RB EMS and MPC-based EMS

		Heat supplied (kWh)		
Season	EMS	R1/R2	R3	R4
Spring	**PID/RB**	1.3	1.5	7.6
		0.6	1.2	3.2
		0.6	1.2	3.6
Winter	**PID/RB**	2.2	2.2	15.6
		1.5	1.3	11.4
		1.5	1.3	11.4

		Computation time (s)		
Season	EMS	R1/R2	R3	R4
Spring	**PID/RB**	36	81	22
		2891	2827	3072
		7344	7952	5330
Winter	**PID/RB**	34	47	23
		5185	2754	2848
		11330	15751	9047

		Constraint deviation (°C/h)		
Season	EMS	R1/R2	R3	R4
Spring	**PID/RB**	0.05	0.01	0.20
		0	0	0
		0	0	0
Winter	**PID/RB**	0.20	0.05	0.66
		0	0	0
		0	0	0

Results (for 3-day simulation)

- **EMS** and **EMS** satisfy comfort constraints
- **FCU energy consumption** and **time of use are both reduced** with **EMS**
- **EMS** and **EMS** have the same energy efficiency
- **EMS** has a lower computation time than **EMS**

→ advantage to **EMS**

III/ Thermal resources management

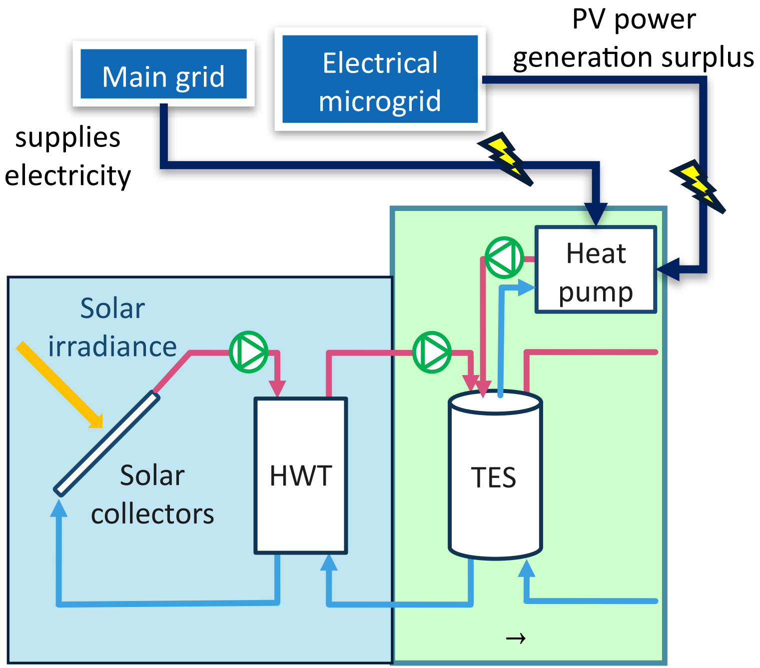
1) Optimization-free MPC-based EMS (EMS)

Objectives

- reduce the economical cost
- **interaction between the electrical microgrid and the thermal microgrid via the photovoltaic power generation surplus**

Strategies

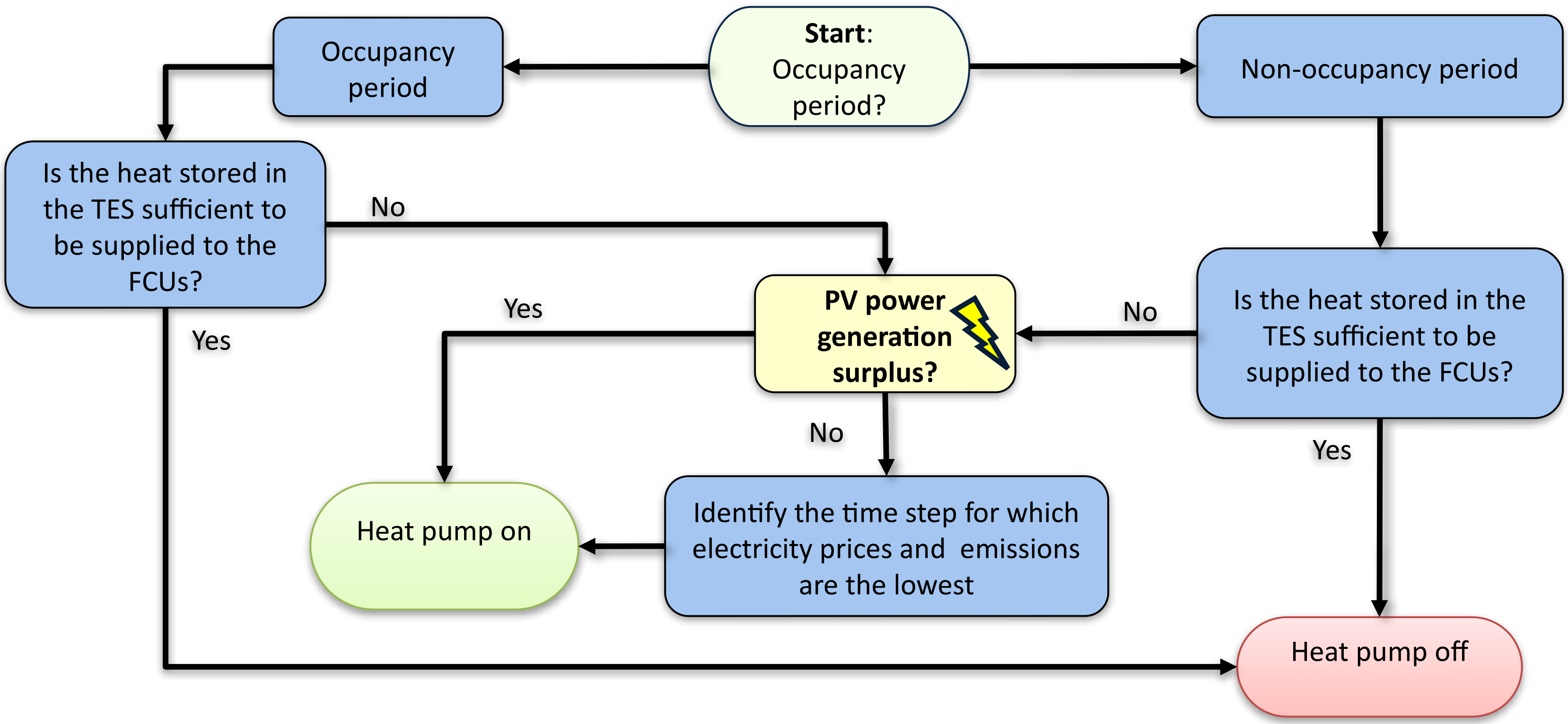
- **turn on the heat pump** when **electricity prices** and when **emissions are low**
- **turn on the heat pump** in case of a **photovoltaic power generation surplus** coming from the electrical microgrid



LNEG thermal microgrid: MPC control

1) Optimization-free MPC-based EMS (EMS)

Algorithm process considering PV power generation surplus:

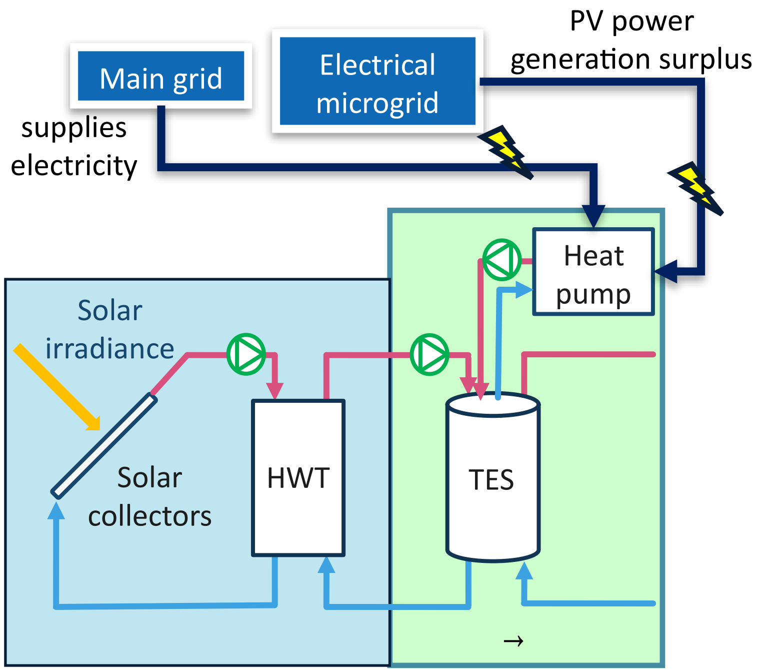


III/ Thermal resources management
2) Optimization-based MPC-based EMS (EMS)

Objectives

- reduce economical cost
- **reduce the carbon footprint**
- maintain water temperature in the TES above 38°C

Optimization problem



LNEG thermal microgrid: MPC control

Normalized electricity purchase tariff and carbon dioxide emissions:

: power furnished by the main grid (kW)

: objective function of the resources subsystem

: optimal time step to turn off/on the Heat pump

: normalized electricity purchase tariff (c€/kWh)

: normalized emission from the main grid production ()

: normalized electricity purchase tariff and emissions

: soft constraint on TES water temperature

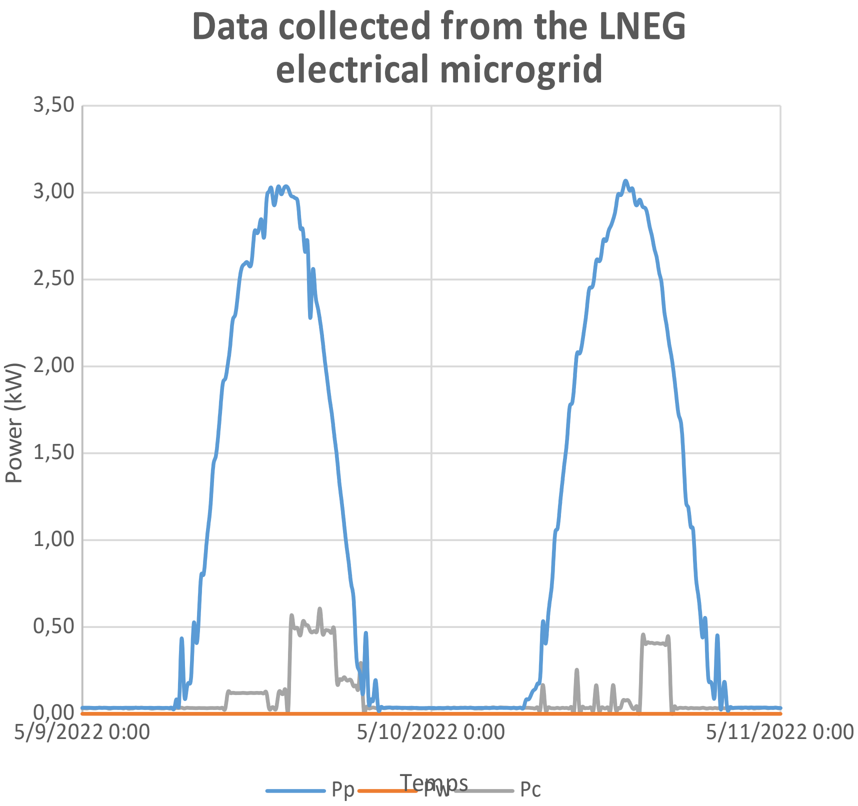
III/ Thermal resources management

2) Optimization-based MPC-based EMS (EMS)

Take advantage of the PV power generation surplus to turn on the heat pump:

Maintain the water temperature in the layer of the TES above 38°C during occupancy periods:

if °C during occupancy period, then



: power consumption (kW)

: PV power generation (kW)

: wind turbine power generation (kW)

: PV power generation surplus (kW)

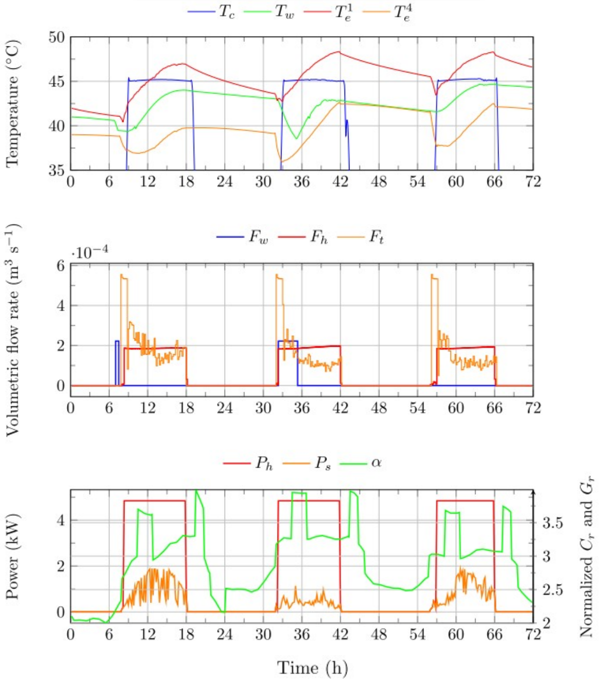
: heat pump power consumption (kW)

: temperature of the TES at layer

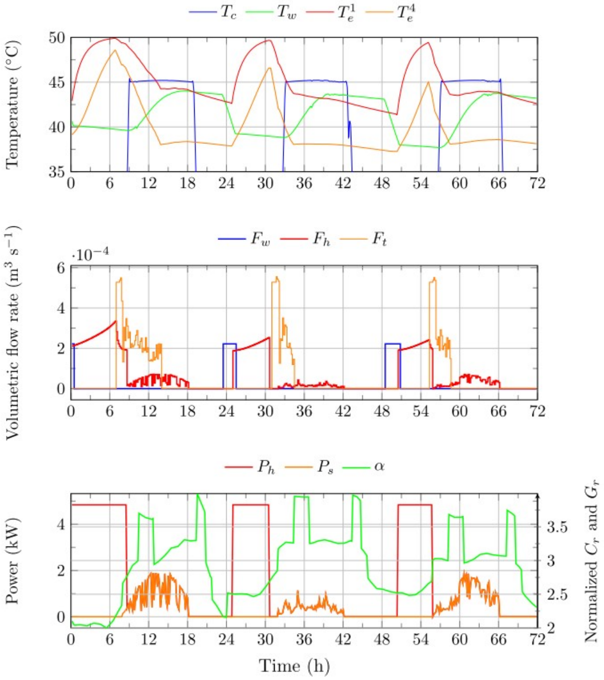
III/ Thermal resources management

3) Comparison between PID/RB EMS and MPC-based EMS

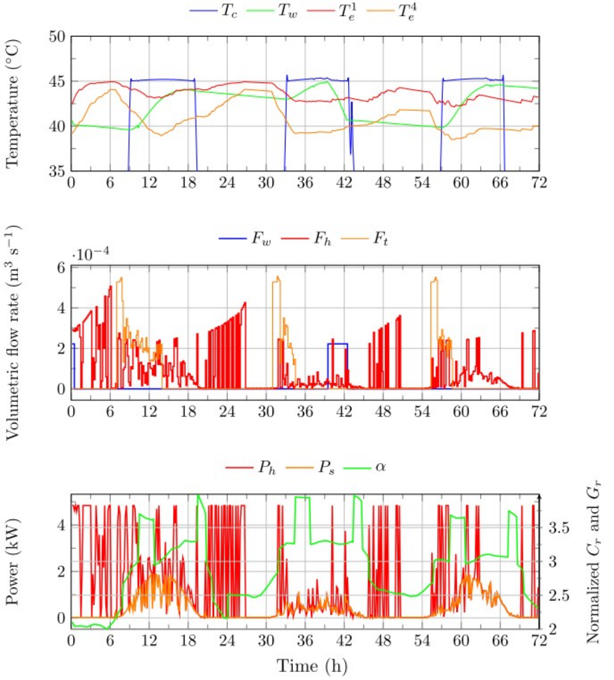
PID/RB EMS



EMS



EMS



Observations (3 winter days created in simulation from real data)

- PID-RB EMS turns on the heat pump when α is high
- EMS and EMS turn on the heat pump when α is low

III/ Thermal resources management

3) Comparison between PID/RB EMS and MPC-based EMS

(kW)	EMS	Electricity bill (€) Winter	Electricity bill (€) Spring
Without PV surplus	**PID/RB**	26.36	13.41
		14.08	0.42
		13.54	0.31
With PV surplus	**PID/RB**	21.91	7.53
		12.34	0.42
		11.18	0.35

(kW)	EMS	emissions (kgCO2) Winter	emissions (kgCO2) Spring
Without PV surplus	**PID/RB**	55.8	25.9
		35.6	0.9
		32.3	0.7
With PV surplus	**PID/RB**	46.5	14.4
		31.7	0.9
		27.8	0.7

(kW)	EMS	Total constraint deviation (°C/h) Winter	Total constraint deviation (°C/h) Spring
Without PV surplus	**PID/RB**	1.43	0.19
		0	0
		0	0
With PV surplus	**PID/RB**	1.41	0.06
		0	0
		0	0

(kW)	EMS	Computation time (s) Winter	Computation time (s) Spring
Without PV surplus	**PID/RB**	126	179
		2824	1950
		182238	154918
With PV surplus	**PID/RB**	157	176
		2566	2669
		179431	143839

Results (for 3-day simulation)

- the quantity of electricity bought and the emissions decrease with **EMS** and **EMS** compared to **PID/RB EMS**
- **EMS** is better than **EMS**
- the constraint of 38°C is always satisfied with **EMS** and **EMS**
- the computation time is lower with **EMS** compared to **EMS**

→ **EMS** is a better solution for implementation

IV/ Energy management in case of MG islanding

1) Configurations and scenarios

Scenarios (4-day simulation)

1. MG islanding from 6 PM on day 1 until the end of day 4
2. MG islanding from 1 PM on day 1 until 1 PM on day 3
3. MG islanding from 8 AM on day 1 until 8 AM on day 2

Configurations

4. , , batteries 2.69 kW/10 kWh
5. , , batteries 2.69 kW/10 kWh
6. , , batteries 2.69 kW/10 kWh
7. , , batteries 5 kW/15 kWh

Thermal comfort constraints (R1, R2, R3 and R4)

8. 21°C
9. 19°C

TES constraints (layer)

10. 38°C
11. 36°C

Objectives

- reduce economical cost
- **reduce the carbon footprint**
- maintain water temperature in the TES above 38°C
- satisfy thermal comfort constraints

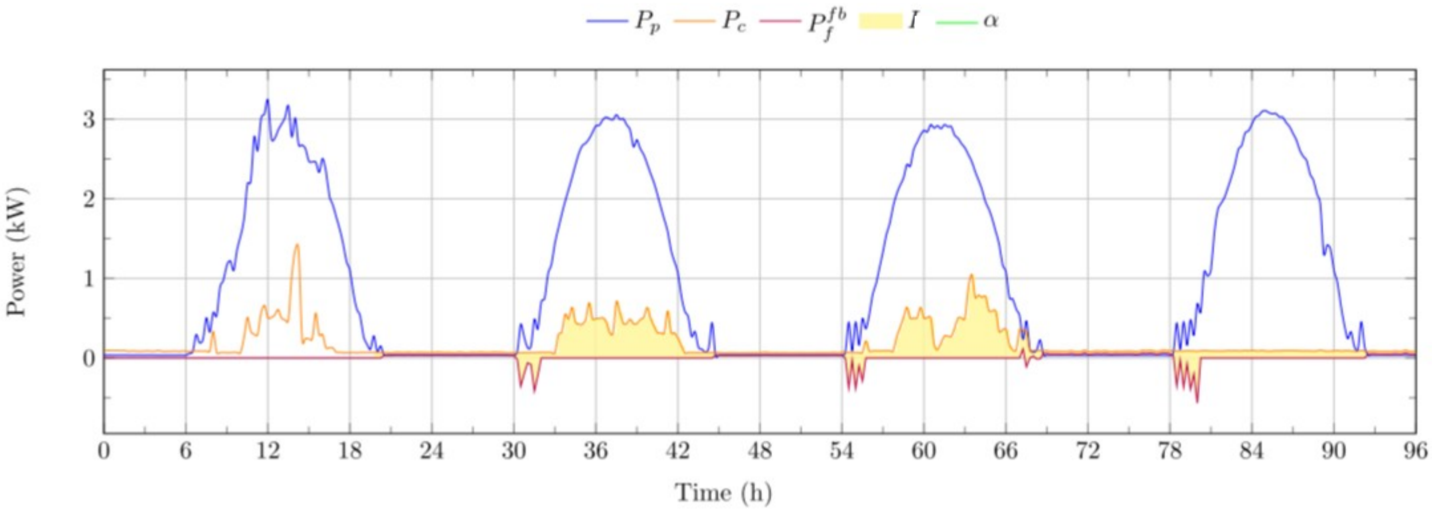
Comparative study

EMS

PID/RB EMS

Islanding evaluation criteria

IV/ Energy management in case of MG islanding
2) Electrical microgrid islanding results



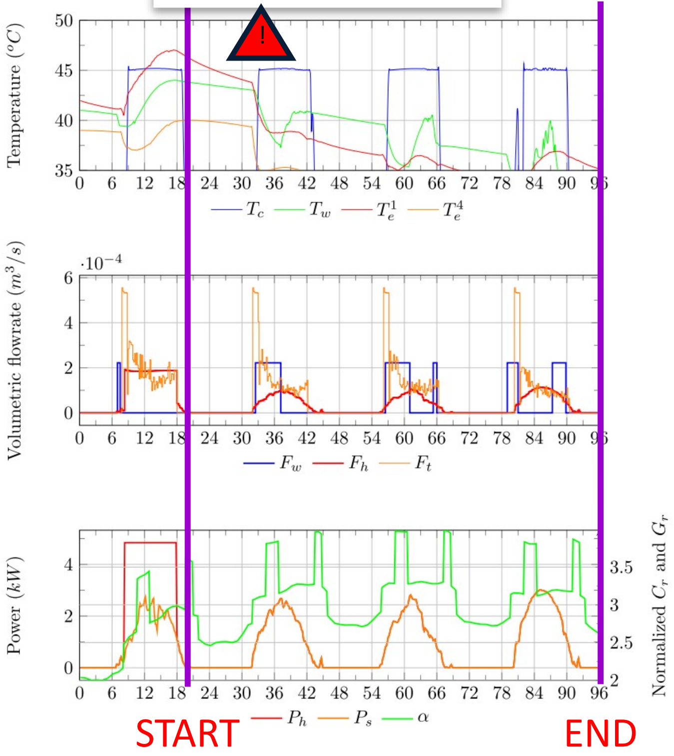
Observations (4-day simulation in winter)

- islanding is always satisfied, regardless of the configuration or the scenario
- small bank of batteries ⟶ PV power generation surplus increases

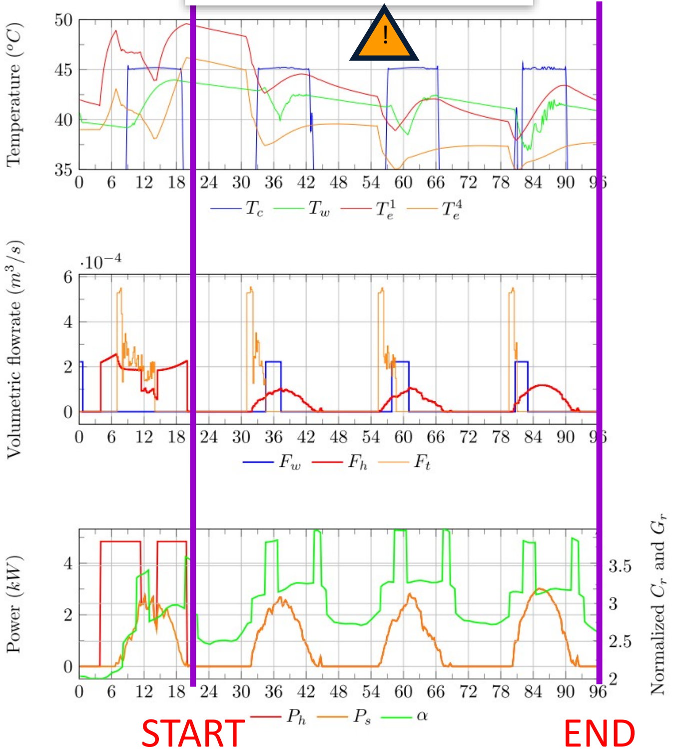
IV/ Energy management in case of MG islanding

3) Multi-energy microgrid islanding results

PID-RB EMS



EMS



EMS stores heat at better instants than **PID/RB EMS**, has lower heat consumption and **takes advantage** of its ability to anticipate the TES constraints related to **islanding**

IV/ Energy management in case of MG islanding

3) Multi-energy microgrid islanding results

Observations for thermal resource management

- **EMS** is better when it comes to satisfy the TES constraints and heat the water stored in the TES using cheap and green electricity

- **EMS** isn't able to correctly manage successive occupancy periods during islanding (only the first one is well managed) for scenario 2, with and

- for scenario 2, with and , **EMS** anticipates the rooms heating using the heat pump → the rooms are heated before solar collectors can heat the water in the TES; this is not the case with **PID/RB EMS**

		C_H							
		$T_r = 21, T_{e,4} = 38$		$T_r = 21,\ T_{e,4} = 36$		$T_r = 19, T_{e,4} = 38$		$T_r = 19, T_{e,4} = 36$	
Is.	Cf.	$\text{MPC}_{\overline{\text{opt}}}$	PID/RB	$\text{MPC}_{\overline{\text{opt}}}$	PID/RB	$\text{MPC}_{\overline{\text{opt}}}$	PID/RB	$\text{MPC}_{\overline{\text{opt}}}$	PID/RB
1	1	671	7671	1020	9470	25	48	2	8
	2	706	8295	1125	9739	34	137	0	0
	3	559	7964	997	9585	73	74	5	18
	4	561	7970	999	9601	75	77	2	21
2	1	1411	6188	1353	8150	168	48	9	8
	2	1492	6795	1550	8447	395	125	0	0
	3	1488	6414	1414	8258	256	103	21	61
	4	1329	6414	1414	8258	256	103	21	61
3	1	1212	3819	1370	5865	95	158	4	47
	2	1515	4219	1588	6238	211	239	0	0
	3	1297	3965	1449	5967	140	241	15	63
	4	1287	4048	1442	5960	161	226	14	61

IV/ Energy management in case of MG islanding
3) Multi-energy microgrid islanding results

Observations for combined thermal resource and thermal comfort management

- thermal comfort constraints are always satisfied with **EMS** whereas they are not with **PID/RB EMS**
- **EMS** is always better than **PID/RB EMS** regarding thermal resource and thermal comfort management

→ **EMS** is a better solution for implementation

		C_T							
		$T_r = 21, T_{e,4} = 38$		$T_r = 21,\ T_{e,4} = 36$		$T_r = 19, T_{e,4} = 38$		$T_r = 19, T_{e,4} = 36$	
Is.	Cf.	$\mathrm{MPC}_{\overline{\mathrm{opt}}}$	PID/RB	$\mathrm{MPC}_{\overline{\mathrm{opt}}}$	PID/RB	$\mathrm{MPC}_{\overline{\mathrm{opt}}}$	PID/RB	$\mathrm{MPC}_{\overline{\mathrm{opt}}}$	PID/RB
1	1	671	8457	1020	10360	25	495	2	513
	2	706	9080	1125	10628	34	583	0	505
	3	559	8749	997	10474	73	521	5	523
	4	561	8756	999	10491	75	524	2	526
2	1	1411	6973	1353	9039	168	495	9	513
	2	1492	7579	1550	9337	395	571	0	505
	3	1488	7200	1414	9147	256	550	21	566
	4	1329	7200	1414	9147	256	550	21	566
3	1	1212	4605	1370	6755	95	605	4	553
	2	1515	5004	1588	7128	211	686	0	505
	3	1297	4750	1449	6856	140	688	15	568
	4	1287	4834	1442	6849	161	673	14	566

Conclusion and perspectives

Multi-energy microgrid management results

	PID-RB EMS	EMS	EMS
Thermal comfort constraints	Not always satisfied	Always satisfied	Always satisfied
Energy consumption	-	Reduced	Reduced
Economical cost	-	Reduced	Reduced
emissions	-	Reduced	Reduced
Thermal constraints	Not always satisfied	Always satisfied	Always satisfied
PV power generation surplus	All surplus used	All surplus used	All surplus used
TES constraints during islanding	Rarely satisfied	Satisfied in a better way most of the time	-
Thermal comfort constraints during islanding	Not always satisfied	Always satisfied	-
Computation time	Low	High	Very high
Implementation	Easy	Moderate	Hard

Conclusion and perspectives

Research question

→ will **EMS** provide better results than **PID-RB EMS** regarding **thermal energy management and thermal comfort constraints satisfaction in grid-connected mode and islanded mode**?

Developments

- multi-energy (thermal-electrical) microgrid model
- PID/rule-based (PID-RB) EMS, **EMS** and **EMS** tested in grid-connected mode and islanded mode

Conclusion

- all **EMSs** are able to **take advantage of the PV power generation surplus**
- **EMS** provides better results than PID/RB EMS in grid-connected mode
- **EMS** provides better results than PID/RB EMS for **thermal comfort and thermal energy (except for scenario 2) management in islanded mode**

→: best solution for in-situ implementation as it has low computation time and overall good performance

Perspectives

- enhance
- enhance **EMS** in islanded mode

THANK YOU!

www.improvement-sudoe.eu

www.promes.cnrs.fr

[1] Buzás, J., I. Farkas, A. Biró, and R. Németh. 1998. 'Modelling and Simulation Aspects of a Solar Hot Water System'. *Mathematics and Computers in Simulation* 48 (1): 33–46. https://doi.org/10.1016/S0378-4754(98)00153-0.

[2] Rahman, Aowabin, Amanda Smith, and Nelson Fumo. 2016. 'Performance Modeling and Parametric Study of a Stratified Water Thermal Storage Tank'. *Applied Thermal Engineering* 100. https://doi.org/10.1016/j.applthermaleng.2016.01.163.

[3] A. L. Nash, A. Badithela, and N. Jain, 'Dynamic modeling of a sensible thermal energy storage tank with an immersed coil heat exchanger under three operation modes', *Applied Energy*, vol. 195, pp. 877–889, Jun. 2017, doi: 10.1016/j.apenergy.2017.03.092.

[4] Peter, Woolf. 2020. 'Book: Chemical Process Dynamics and Controls (Woolf)'. Engineering LibreTexts. 19 May 2020. https://eng.libretexts.org/Bookshelves/Industrial_and_Systems_Engineering/Book%3A_Chemical_Process_Dynamics_and_Controls_(Woolf).

[5] Darure, Tejaswinee. 2017. 'Contribution to Energy Optimization for Large-Scale Buildings: An Integrated Approach of Diagnosis and Economic Control with Moving Horizon'. Phdthesis, Université de Lorraine. https://tel.archives-ouvertes.fr/tel-01647139.

[6] S. Stamp, H. Altamirano-Medina, and R. Lowe, 'Measuring and accounting for solar gains in steady state whole building heat loss measurements', *Energy and Buildings*, vol. 153, pp. 168–178, Oct. 2017, doi: 10.1016/j.enbuild.2017.06.063.

[7] A. Garnier, J. Eynard, M. Caussanel, and S. Grieu, 'Low computational cost technique for predictive management of thermal comfort in non-residential buildings', *Journal of Process Control*, vol. 24, no. 6, pp. 750–762, Jun. 2014.