CONTROL AND OPTIMIZATION IN SMART-GRIDS

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Course topics

- Session 1: Introduction to Power systems
  - Context and motivation
  - Power flow analysis
  - Economic dispatch
- Session 2: Renewable sources
  - Stochastic models of variable sources
  - Dispatching random sources
- Session 3: Energy dispatch
  - Risk-limiting dispatch
  - Matlab session

Course topics

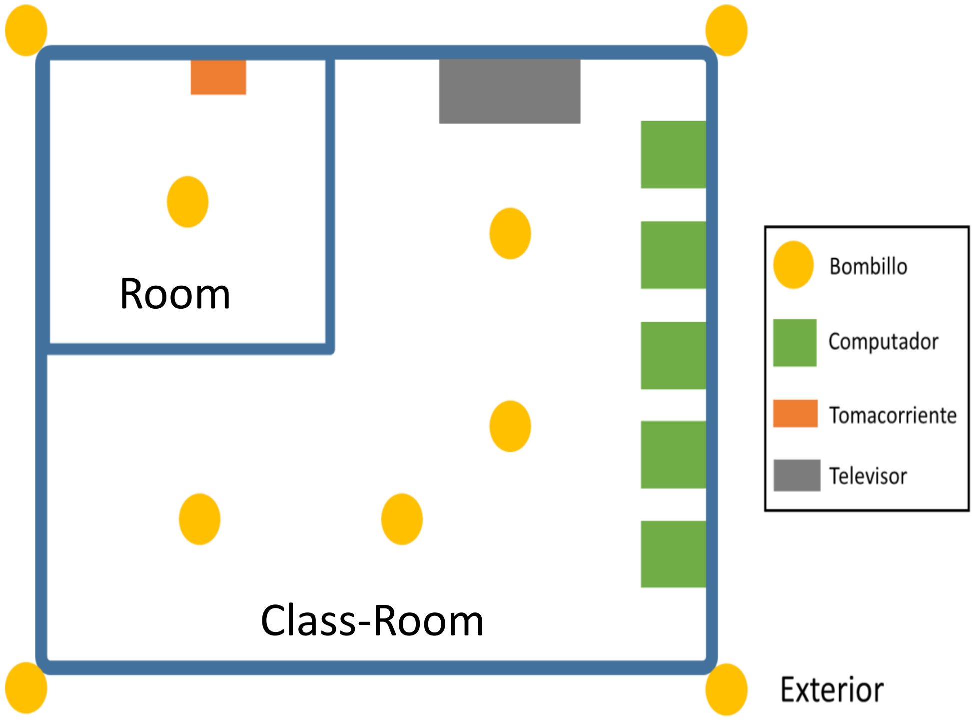
- Session 4: Incentive-based demand response
  - Modeling demand
  - Peak time rebates
  - Contract design for demand response
- Session 5: Flexible loads
  - Modeling flexibility
  - Load dispatch
  - Case study: Electric vehicles
- **Session 6: Micro-grids**
  - **Lean energy concept**
  - **Joint generation and load dispatch**

SOLAR-BASED ENERGY SYSTEM FOR RURAL SCHOOLS IN COLOMBIA

- *School without electric energy in isolated zones.*
- *Negative impact on education quality.*
- *High cost of traditional electrification.*

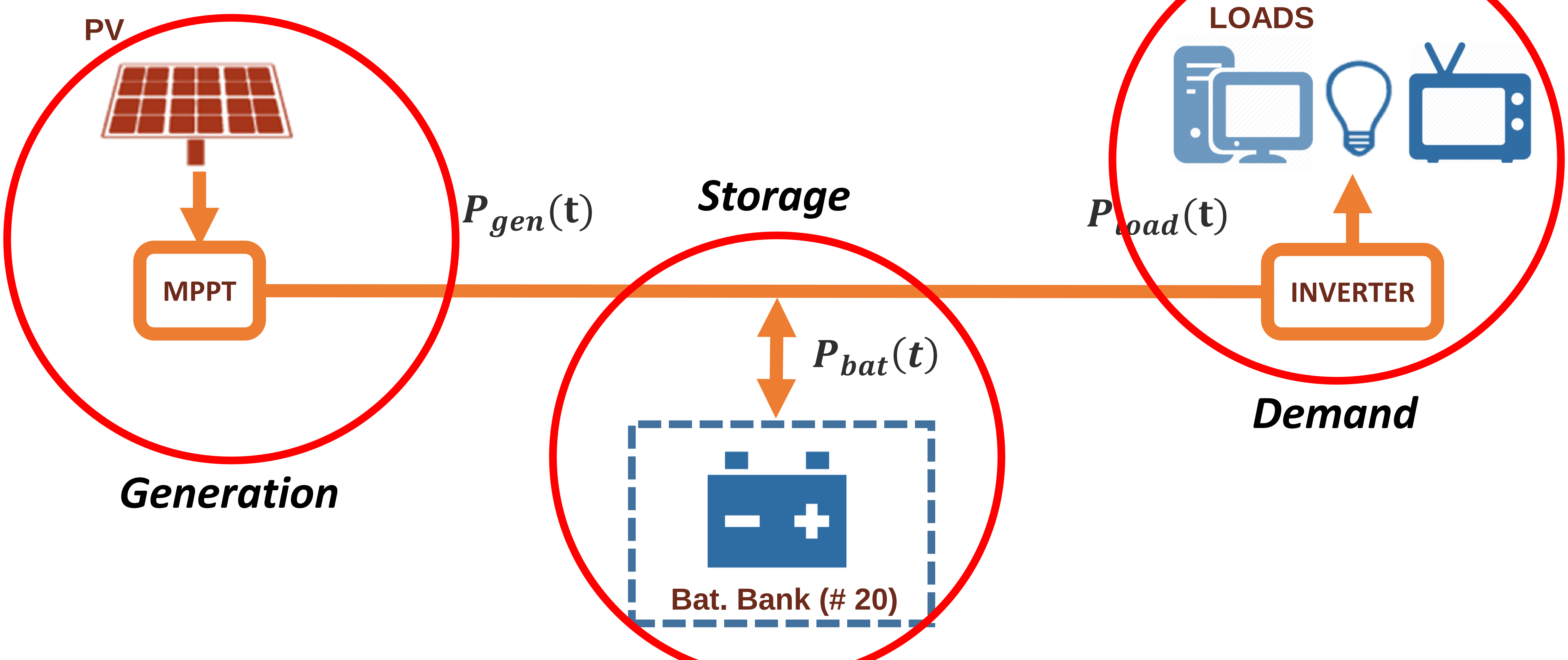
Rural micro-Grid Energy Management

Schools



ELEMENT	Load [Wh]	#
Lights- External	20	4
Lights - Classroom	20	4
PCs	60	5
TV	100	1
Outlet	50	1
Lights - room	20	1

Isolated micro-grid
Solar system



Challenges in isolated systems

- Demand characterization
  - User profile
  - Monte Carlo simulations
  - Worst-case parameters: P… served
- Generation Sizing
  - Renewa… …ical and Seasonal information
  - … on Investment (ROI)
- … Sizing
  - Most costly element
  - Short lifetime if subject to deep discharge

Criterion: Load must always be served!!!!!!!!!

Micro-grid sizing problem

- Given the random behavior of generation and load, the generation and storage systems must have a capacity to ALWAYS satisfy the demand.
- Performance indexes
  - Loss of power supply probability (LPSP):

$$LPSP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t)\Delta t},$$

  - Level of autonomy (LA):

$$LA = 1 - \frac{H_{LOL}}{H_{TOT}},$$

Micro-grid sizing problem

- Traditional sizing methods are too conservative.
- They minimize the probability of not serving all the loads.
- In consequence:
  - High cost of installation
  - Low capacity factor
  - Not attractive from an economic point of view

Energy as a Service Concept

- Users are not buying energy (Power).
- They need SERVICES:
  - Lighting
  - Computer
  - TV
  - Cellphone charging
  - …

- *Do consumers need ALL services available 24h/day?*
- *Would users accept intermittent SERVICES at a lower cost?*
- *What technological issues arise?*

Energy as a Service Concept

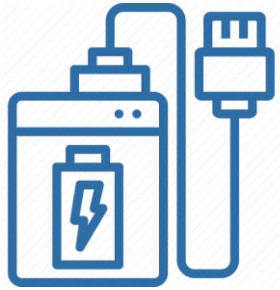
- Users are not buying energy (Power).
- They need SERVICES:
  - Lighting
  - Computer
  - TV
  - Cellphone charging
  - …

Load	Priority		
	Case 1	Case 2	Case 3
Outside lightbulbs	1	1	3
Classroom lightbulb 1	2	2	2
Classroom lightbulb 2	2	1	1
Classroom lightbulb 3	2	1	1
Classroom lightbulb 4	2	1	1
Personal computer 1	3	1	1
Personal computer 2	3	1	1
Personal computer 3	3	1	1
Personal computer 4	3	1	1
Personal computer 5	3	2	1
Classroom TV	3	2	1
Outlet	1	3	3
Bedroom Lightbulb	1	3	3

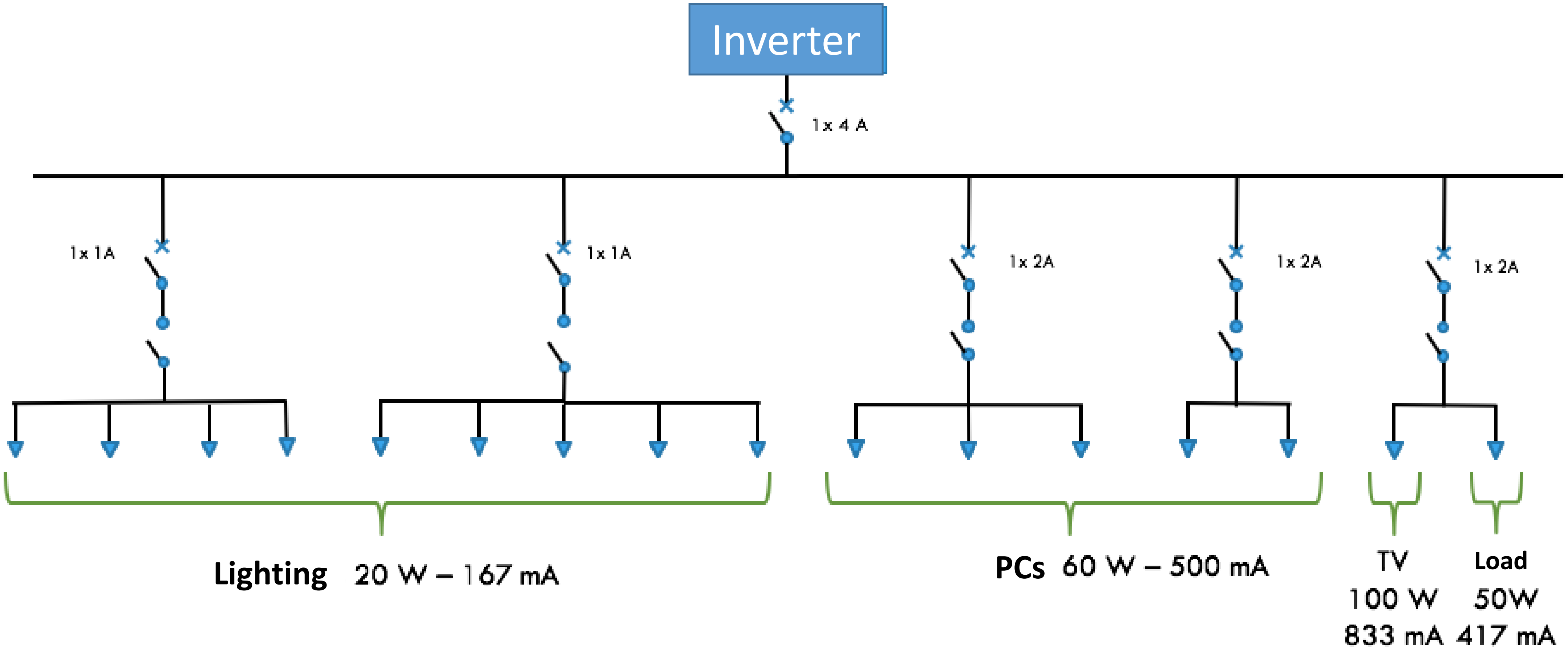
Energy management system (EMS)

To develop an energy management system capable of:

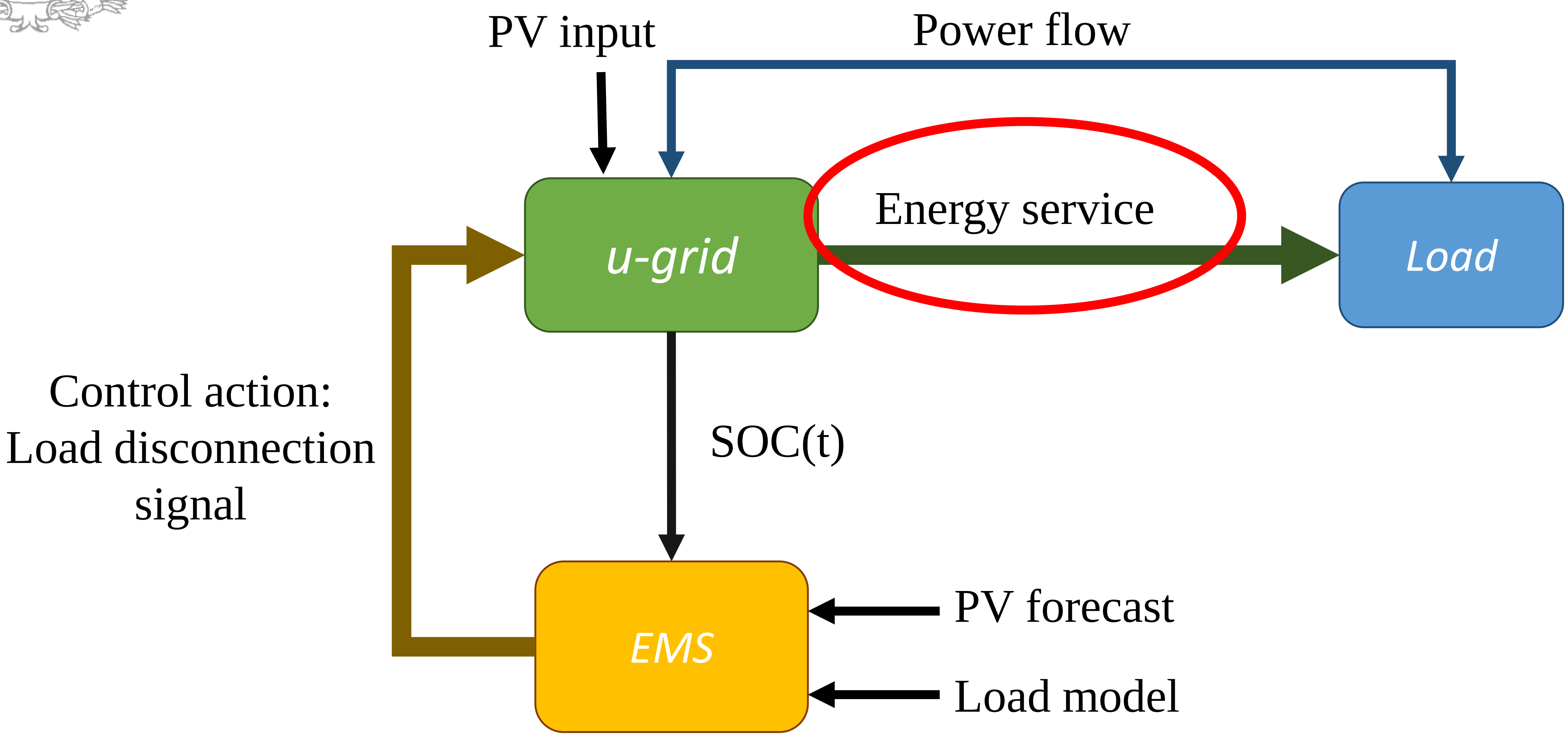
- Supervising the State of Charge of the Battery Bank
- Regulating the Deep of Discharge of the battery bank
- Maximizing the energy service for the users
- Running on a low-complexity embedded system (Raspberry Pi)



Energy management system



Control Architecture



MPC based EMS

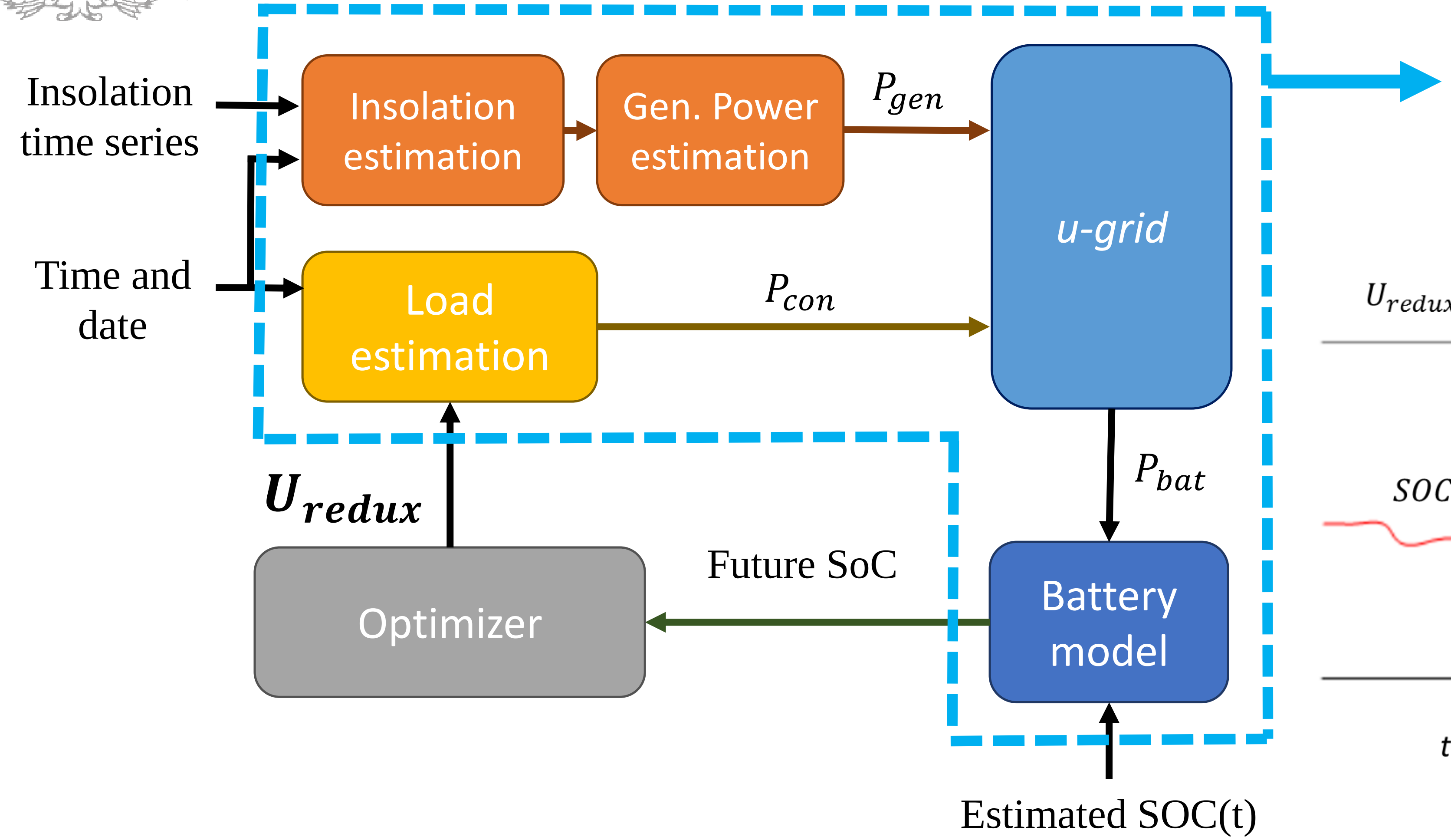
Why MPC?

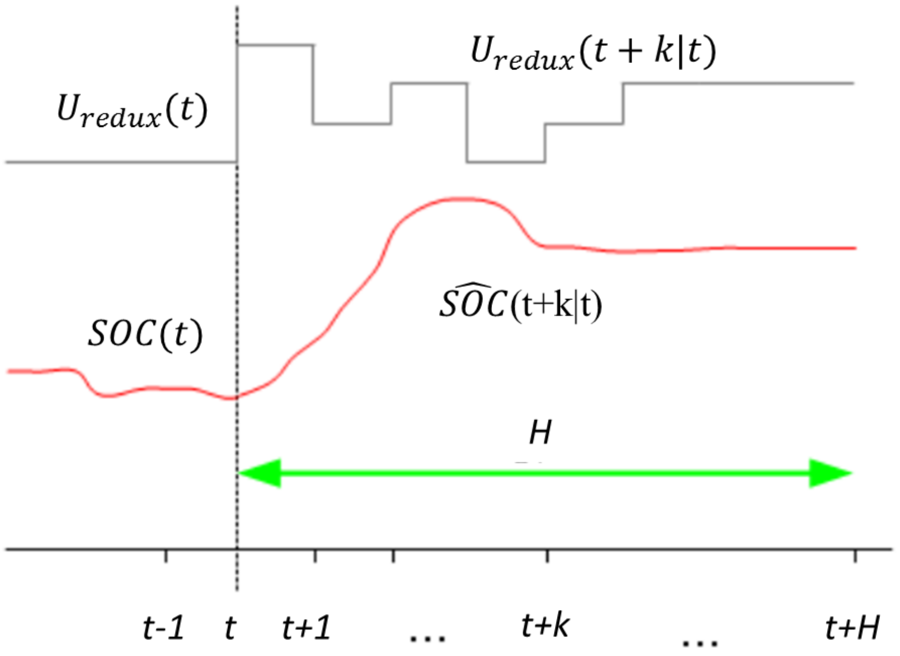
- It is able to handle HARD constraints
- Cost Function minimization (Optimal control approach)

Objectives

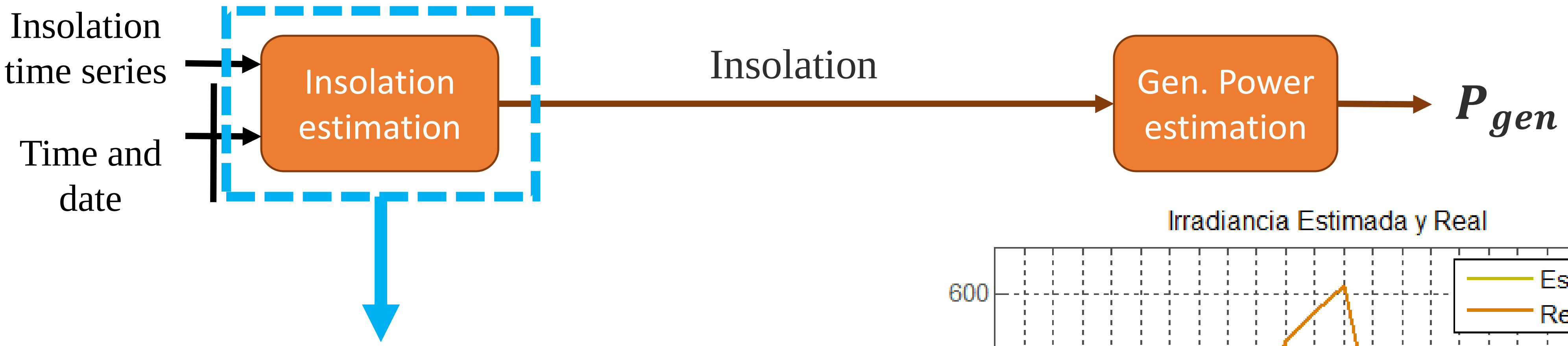
- **Maximize the benefit** generated from the energy service
- **Limit the DoD** of the battery bank in order to gurantee a long life span

MPC Strategy

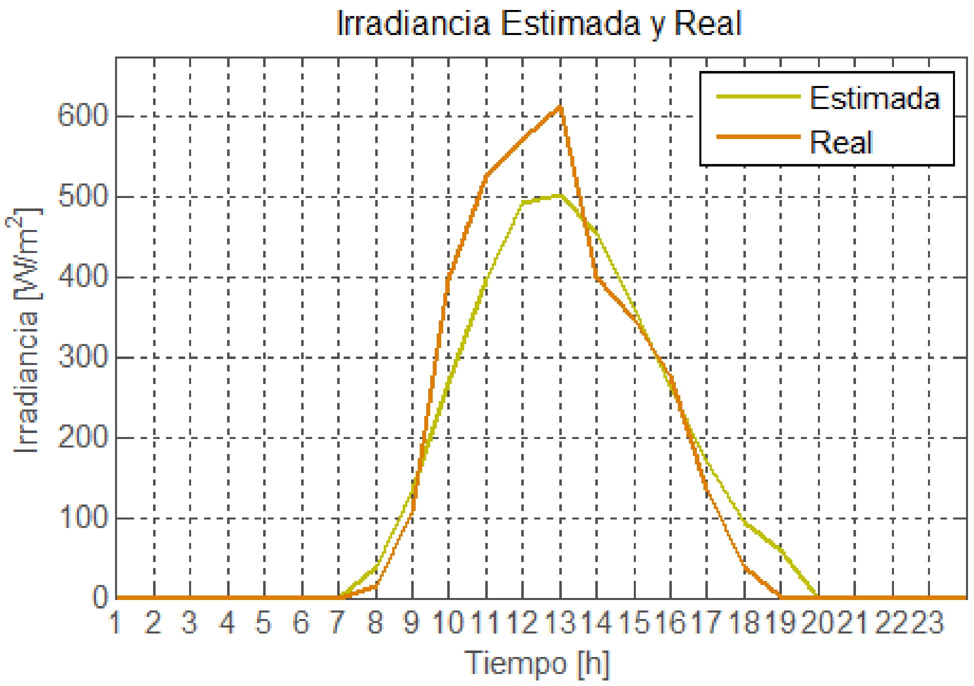




Generation prediction

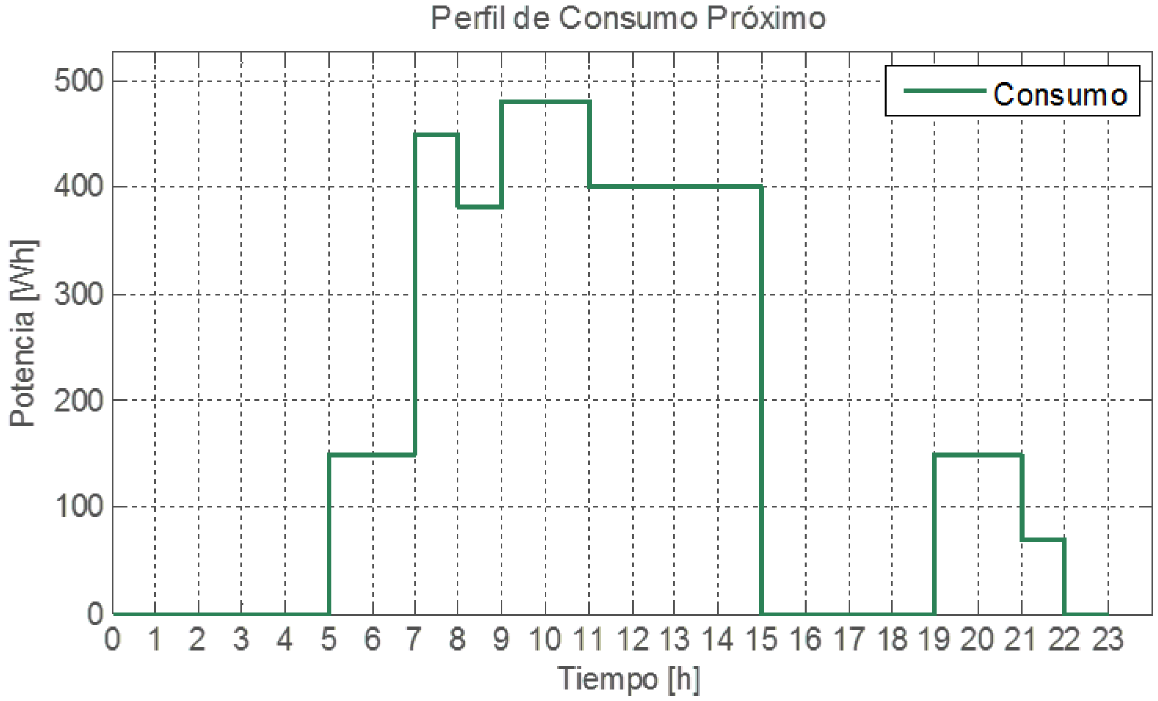


Simple FIR estimator to predict next 12 hours generation

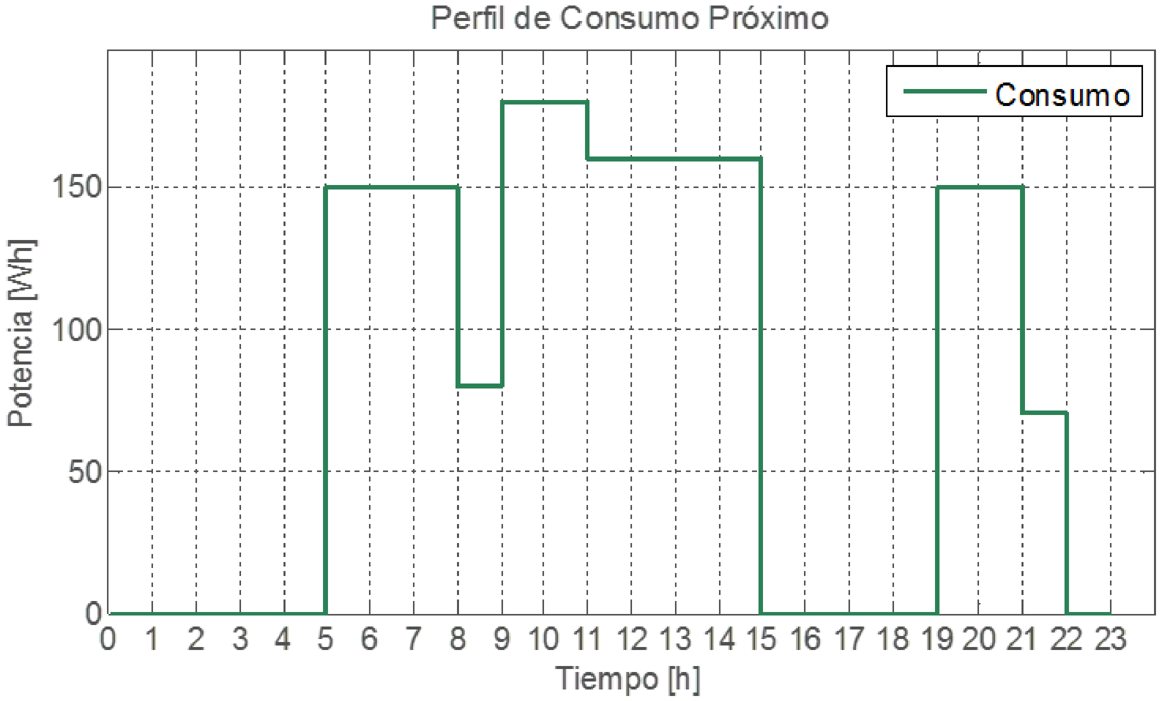


Load Profile

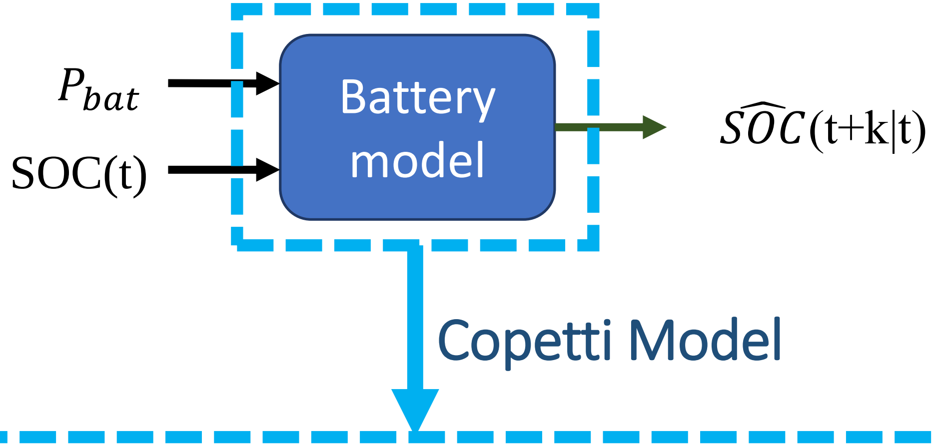
Week Day

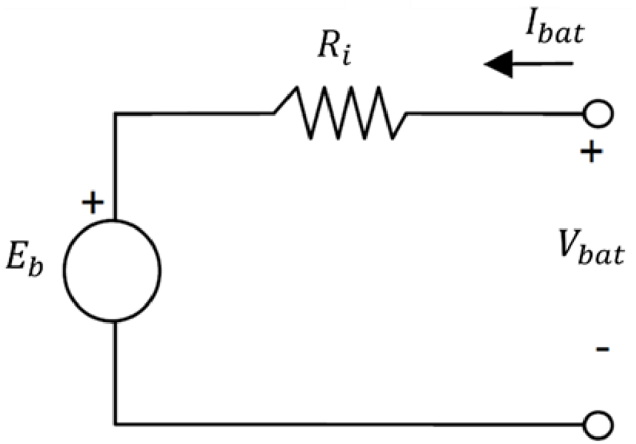


Weekend Day



Battery model



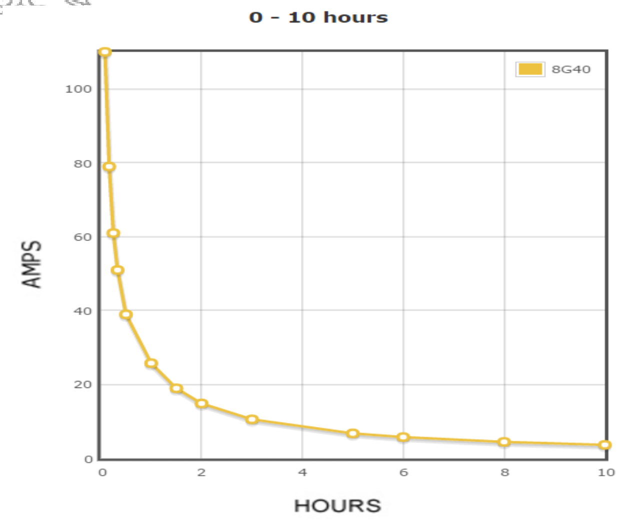


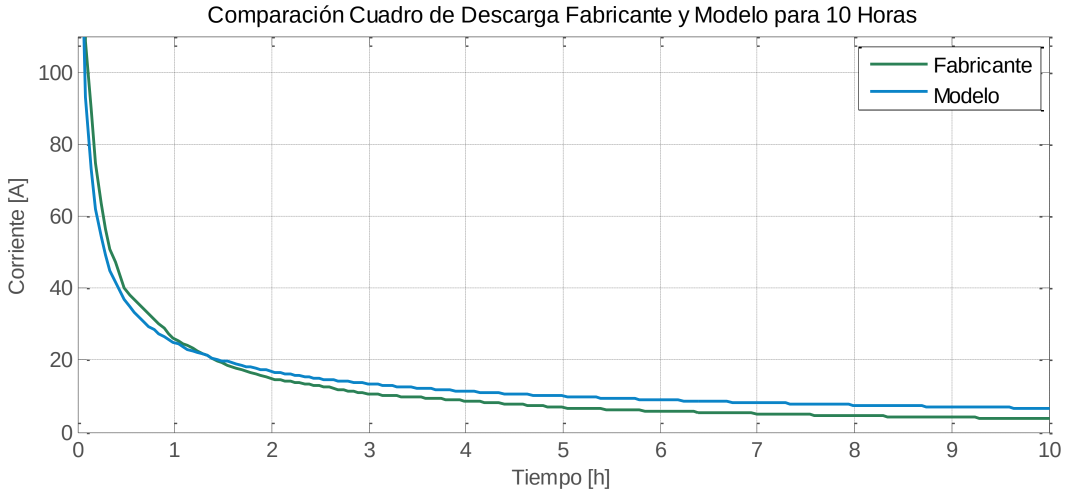
$$\begin{cases} E_b = f(SOC(t)) \\ R_i = f(SOC(\mathrm{t}), I_{bat}, T) \end{cases}$$

$$V_{bat} = E_b + R_i * I_{bat}$$

$$I_{bat}(t) = \frac{P_{bat}(t)}{V_{bat}(t)}$$

Battery model validation



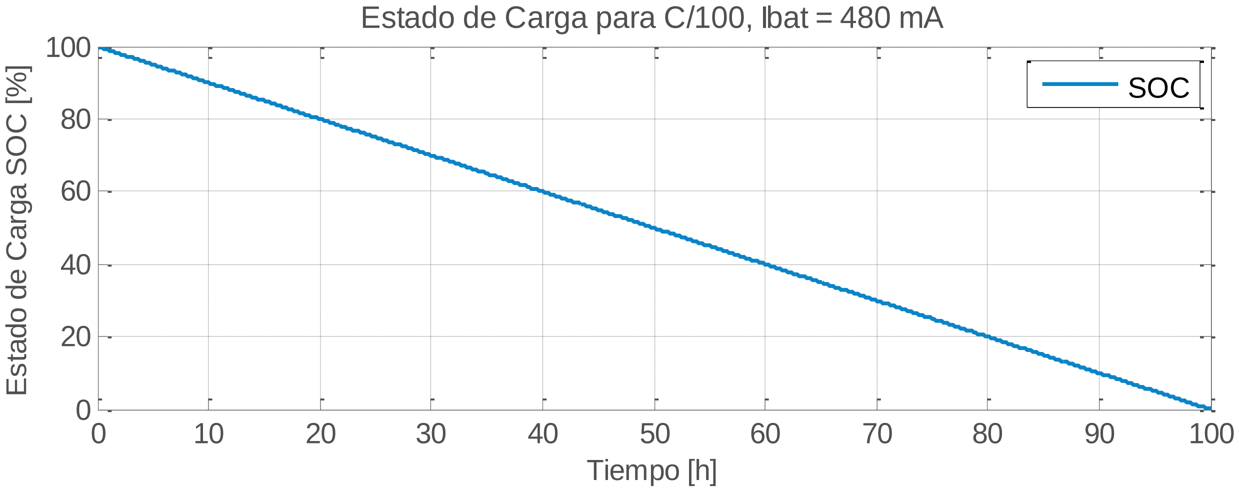


RMS error

8.8 A

SPECIFICATIONS

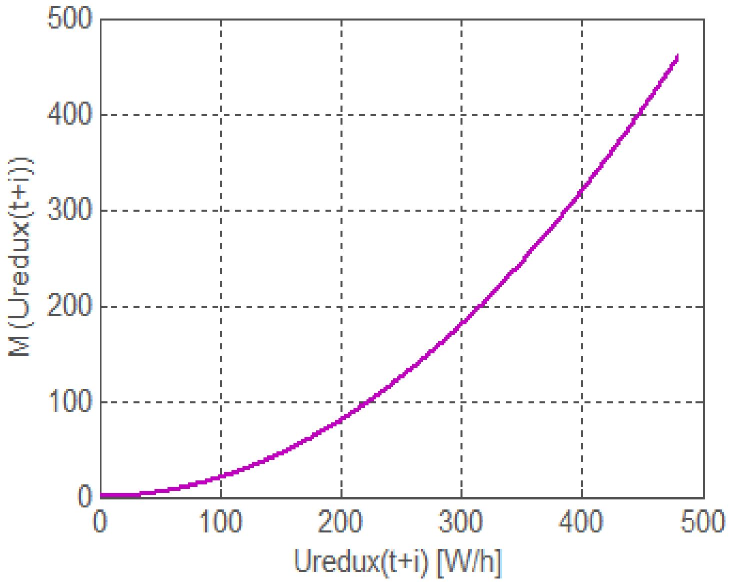
Nominal Voltage (V)	12V
Capacity at C/100	48Ah
Capacity at C/20	40Ah



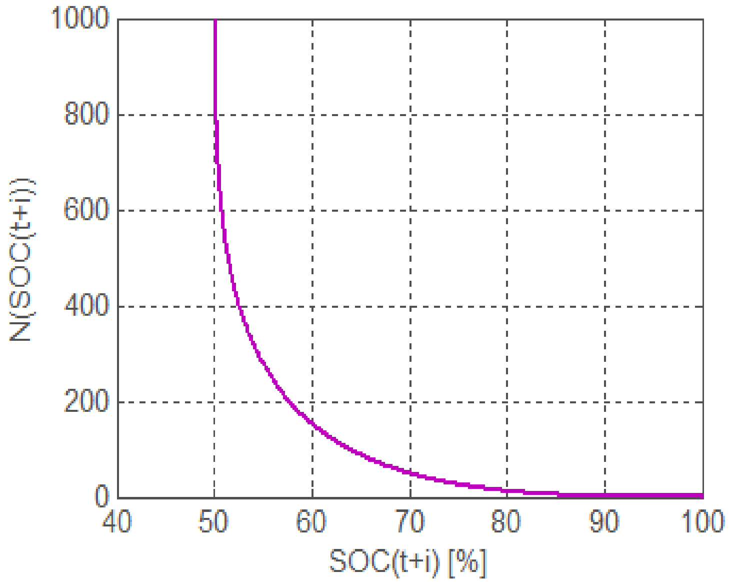
MPC Problem Formulation

$$J(\boldsymbol{U_{redux}}) = \sum_{i=0}^{H} \left[\alpha * M(\boldsymbol{U_{redux}}(t+i)) + \beta * N(\boldsymbol{SOC}(t+i))\right]$$

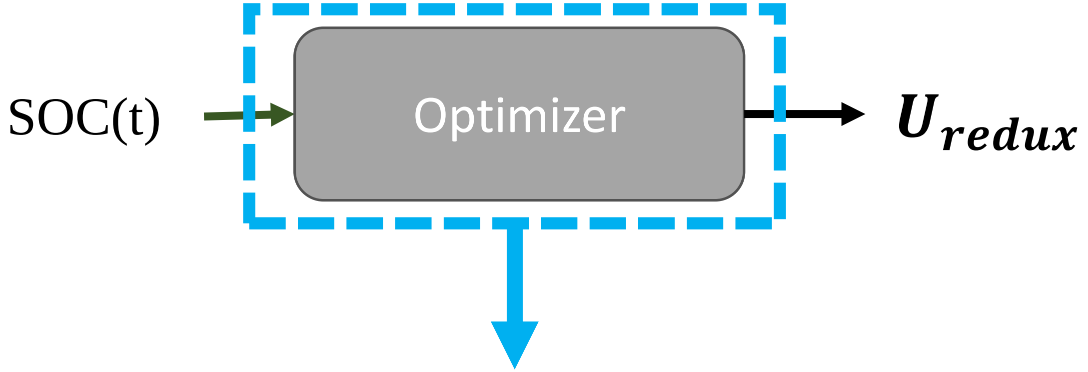
$$M(U_{redux}(t+i)) = U_{redux}(t+i)^2$$



$$N(SOC(t+i)) = [SOC(t+i) - 100]^2 + [\ln(50) - \ln(SOC(t+i) - 50)$$



Optimization problem



$$\min_{U_{redux}} J(U_{redux}) = \sum_{i=0}^{H} \left[\alpha * M\left(U_{redux}(t+i)\right) + \beta * N\left(SOC(t+i)\right) \right]$$

s.t.

Deep of Descharge, $$50 < SOC(t+i)$$

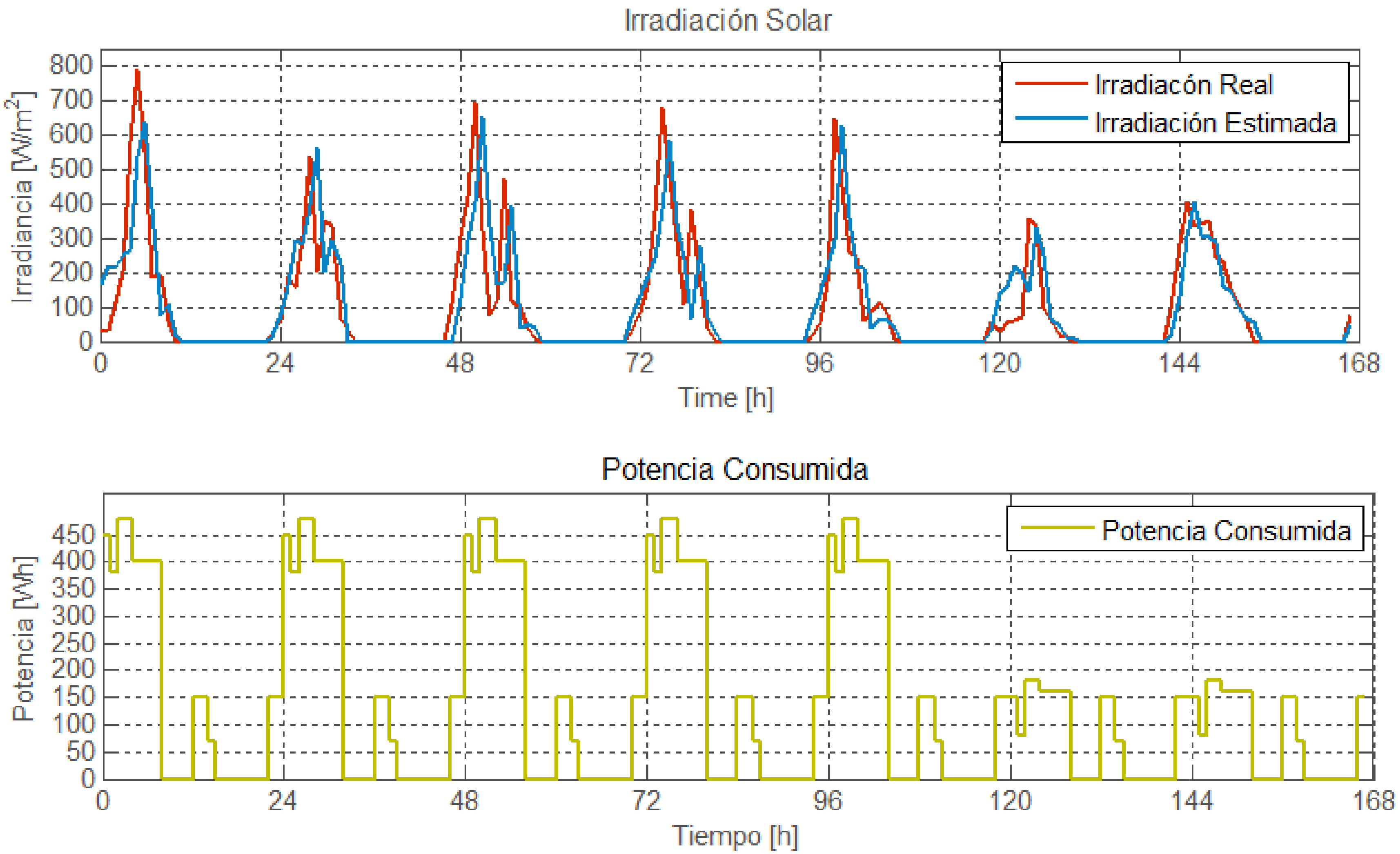
Load curtailment, $$0 < U_{redux}(t+i) < U_{max}$$

SYSTEM EVALUATION

Performance index

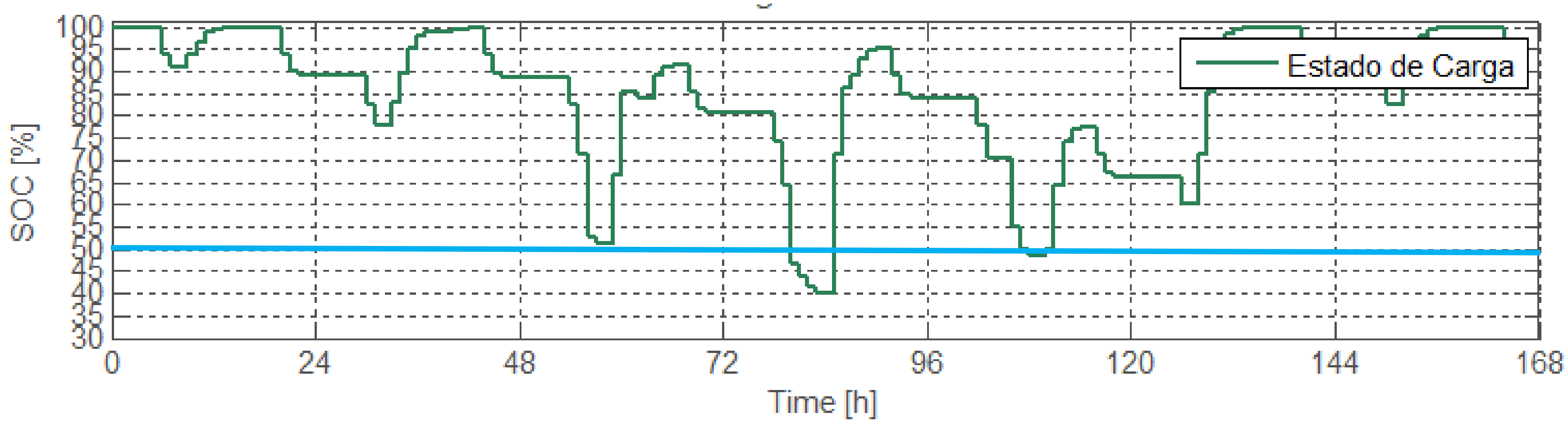
INDEX	DESCRIPTION	FORMULA
C_U	Energy Service cost	$\alpha \sum_{t=0}^{tsim} \sum_{i=0}^{H} M\big(U_{redux}(t+i)\big)$
C_{soc}	Battery usage cost	$\beta \sum_{t=0}^{tsim} \sum_{i=0}^{H} N\big(SOC(t+i)\big)$
$> 50\%$	Binary indicator of SoC level above 50%	$SOC > 50\% \;\; => Yes$ $SOC \leq 50\% \;\; => No$
U_p	Maximun load curtailment	$\max(U_{redux\,t=0}, U_{redux\,t=1}, \ldots, U_{redux\,t=tsim})$

Evaluation conditions (1 week)



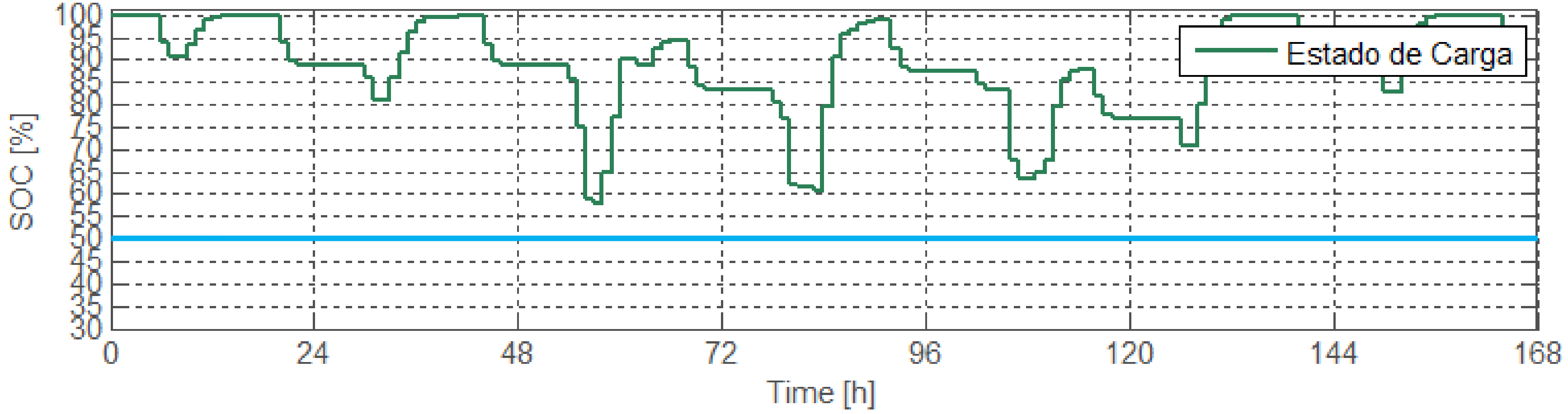
$199.2\ \frac{W}{m^2}$

SoC control



Without control

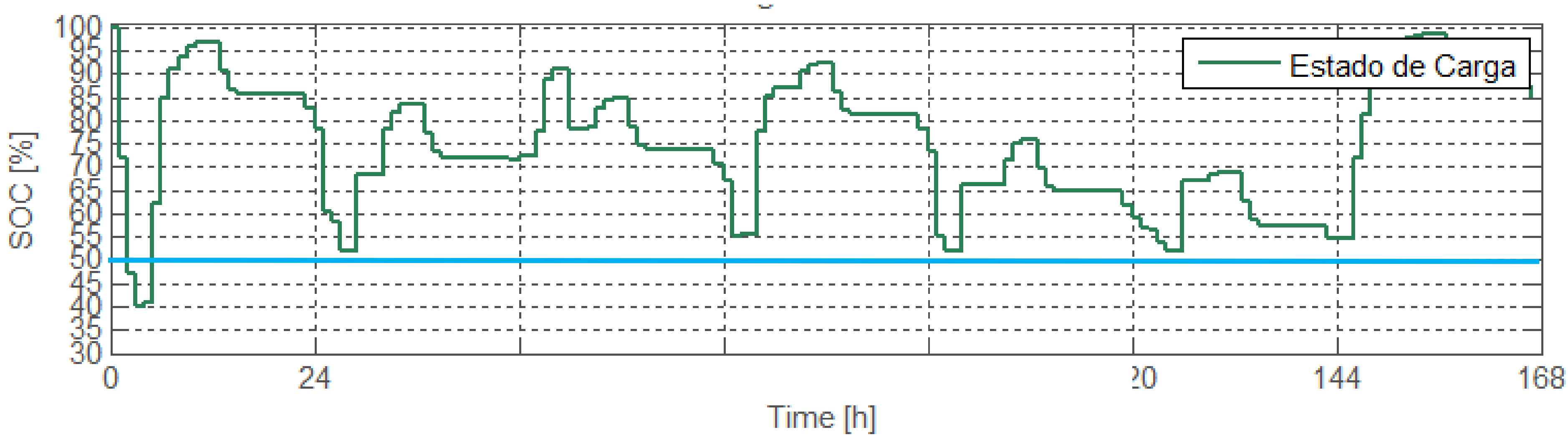
U_p = 0
> 50% = NO



MPC

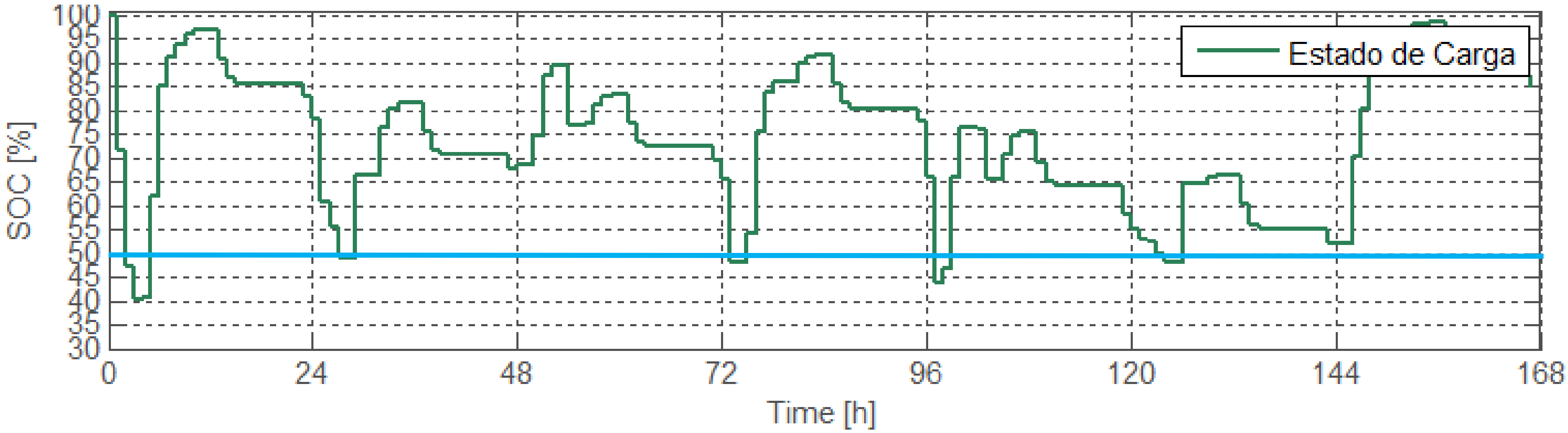
U_p = 110 W
> 50% = OK

Behavior for different prediction horizons



12 hours

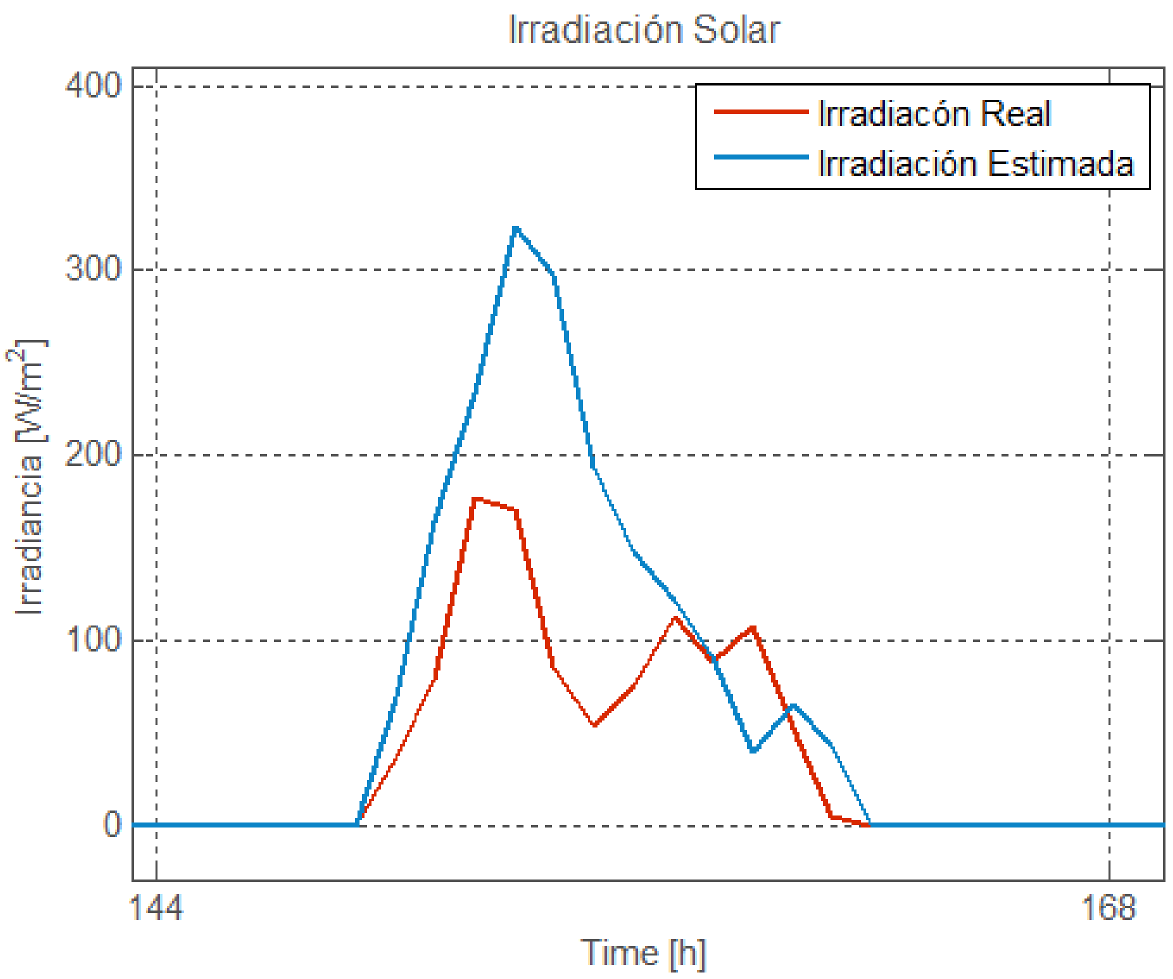
Exc. time:
161.4866 s



6 hours

Exc. tiem:
148.8113 s

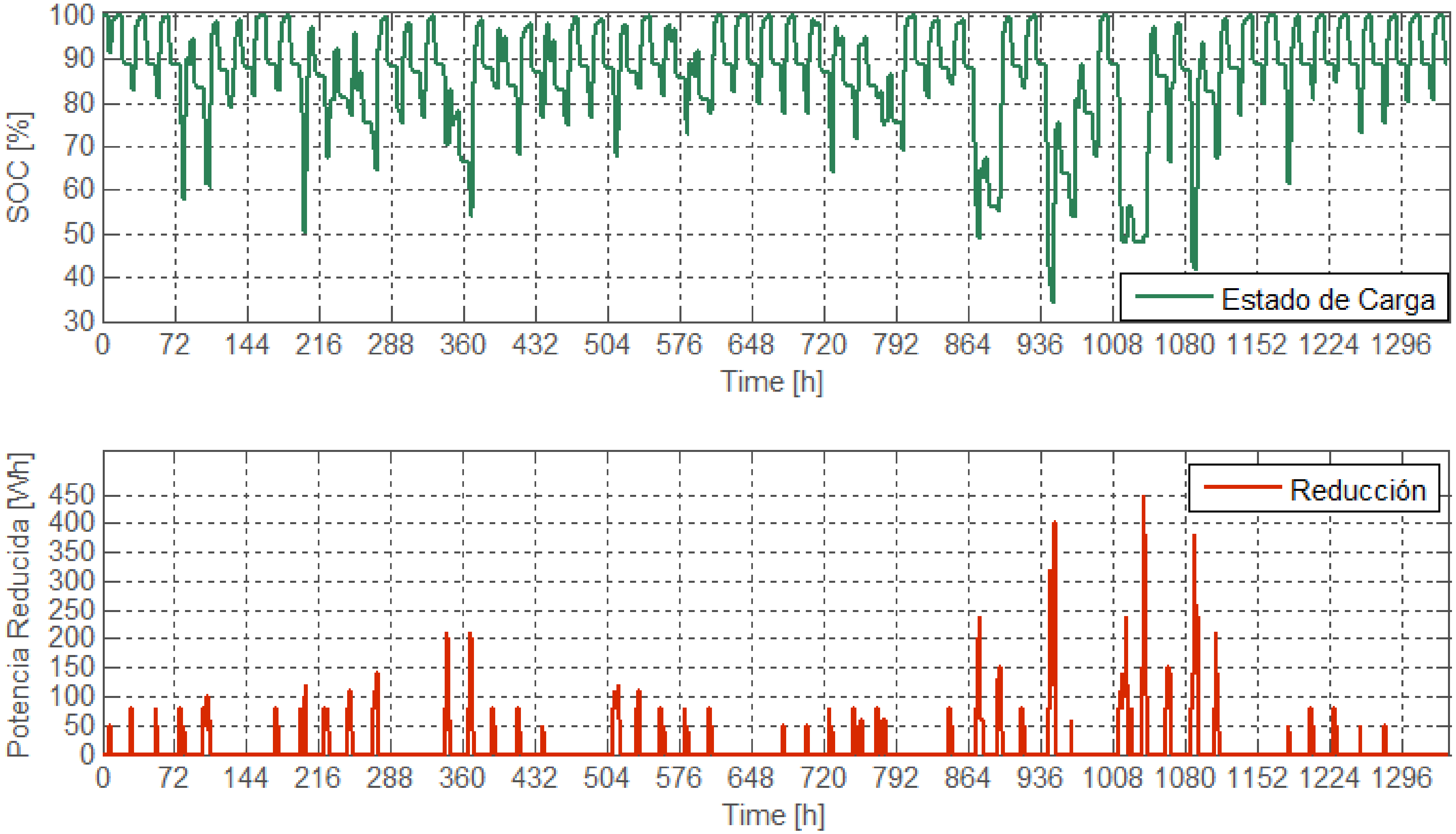
Effect of Insolation estimation error



Effect of Insolation estimation error

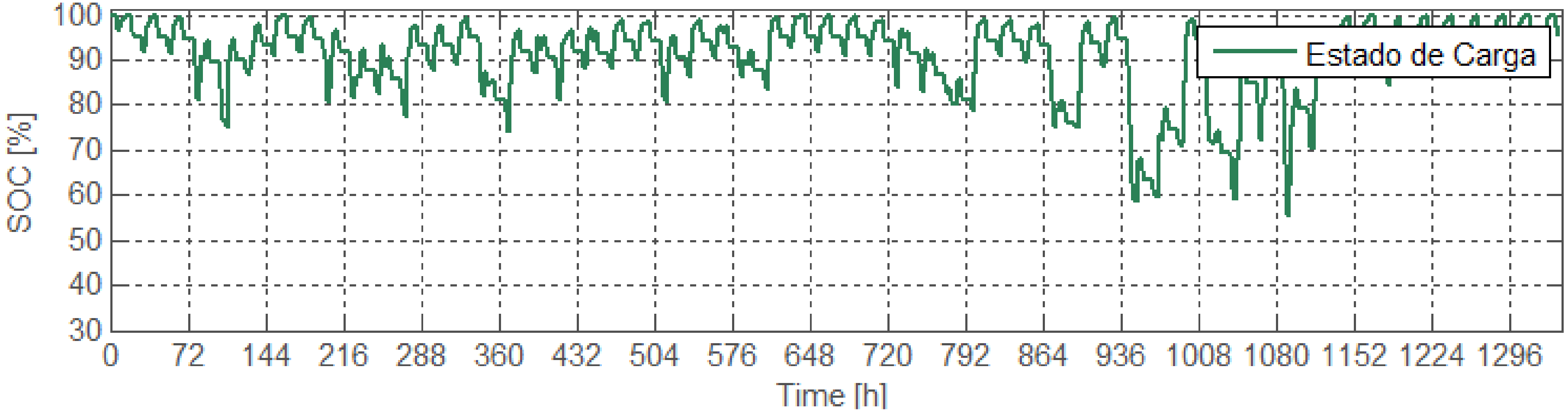
WEEK	# OF OVER-ESTIMATED DAYS	C_U	C_{SOC}	$U_p\ [Wh]$	$> 50\%$
1	1	37,170	2.5305e+05	480	NO
2	2	22,200	9.3055e+04	480	NO
3	0	11,040	8.4360e+04	400	YES
4	0	19,800	1.8736e+05	380	YES
6	1	2,700	4.2326e+04	380	YES

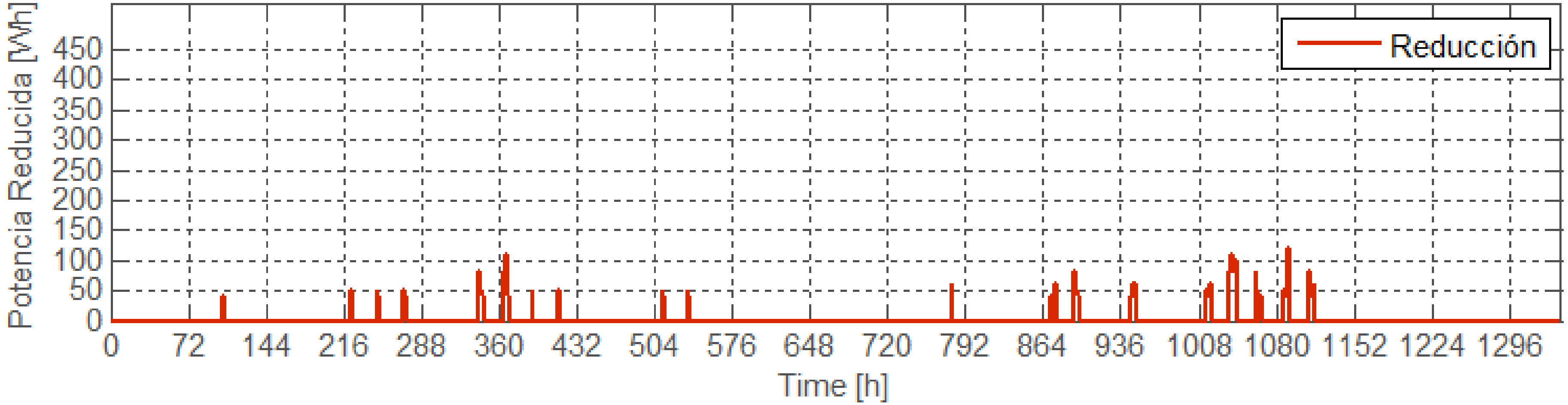
System performance with small battery bank (384 Ah)



C_U = **78180**
C_{soc} = **6.5e+5**
U_p = **450**
$> 50\%$ = **NO**

System performance with big battery bank (720 Ah)

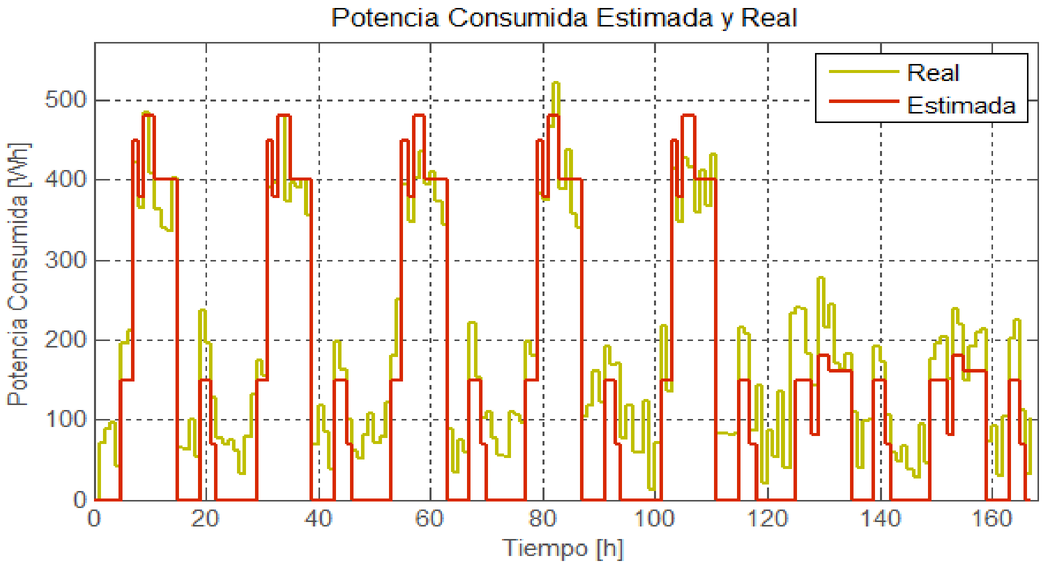




C_U = **7380**
C_{soc} = **2.6e+5**
U_p = **120 W**
$> 50\%$ = **SI**

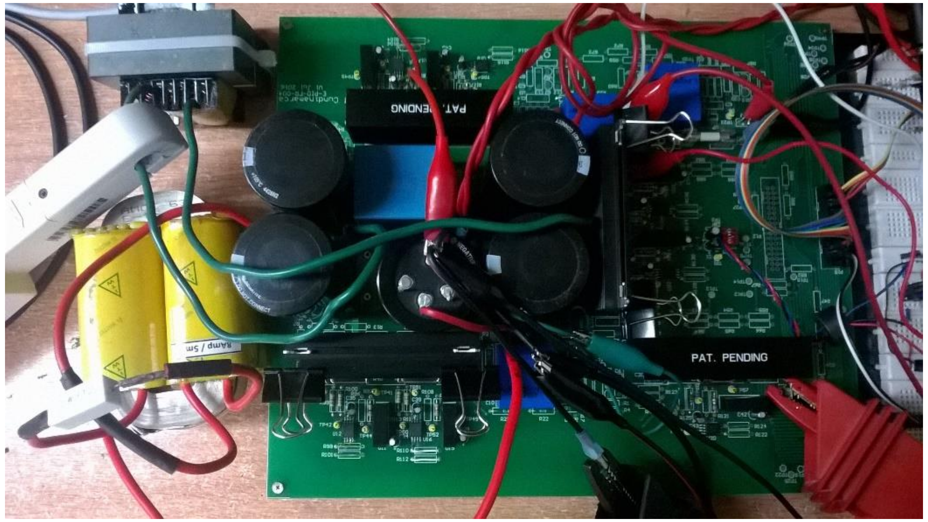
Load uncertainty effect

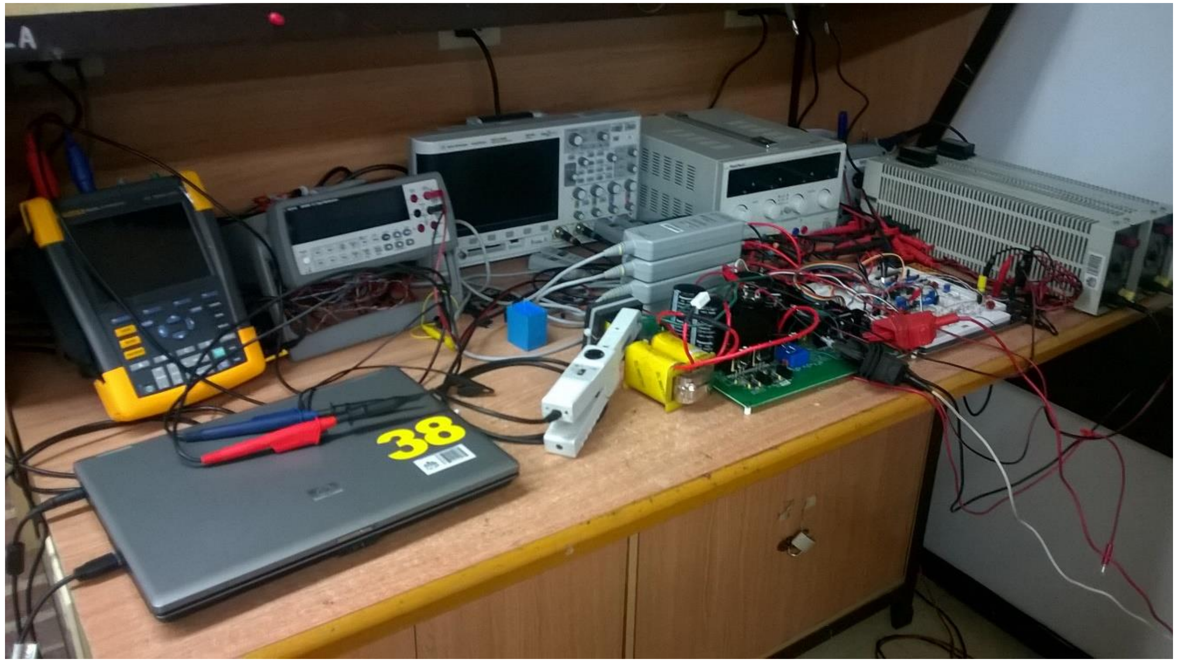
Performance under random variations in load behavior.



LOAD VARIANCE [σ^2]	C_U	C_{SOC}	$U_p\ [Wh]$	$> 50\%$
0.1	9540	2.1065e+05	190	YES
0.2	9480	2.0181e+05	220	YES
0.3	10080	2.1188e+05	230	YES
0.4	15450	2.7330e+05	210	YES
0.5	36060	3.4735e+05	250	NO
0.6	33120	5.6035e+05	220	NO

Power electronics





- Validated in lab. conditions.
- It's able to supply 1kW peak power.
- Low-level PID control
- Digital MPPT strategy

Next steps

- Evaluate performance on field
- Bussines model