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Design and optimization of a standalone photovoltaic system considering panel position, battery lifespan, and cost

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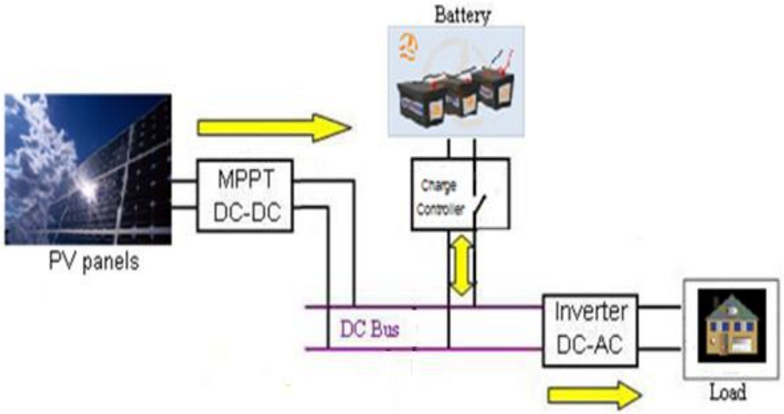

Plan

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- **STANDALONE PHOTOVOLTAIC SYSTEM**
- **DESIGN OPTIMIZATION PROCEDURE**
- **RESULTS AND DISCUSSIONS**
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INTRODUCTION

- Solar Home Systems (SHS) have been promoted as an alternative to grid extension especially for isolated sites. These photovoltaic (PV) systems require batteries, minimal costs, and must be reliable.

- Batteries' size, installation, operation and maintenance are fundamentally different from other energy storage applications.

- In our previous investigations, we considered both ecological and economic costs for the design optimization of a stand-alone hybrid wind-PV power system that included battery storage. Embodied energy is a relevant objective function where the life cycle of the components is considered.

- For this new investigation, we propose to thoroughly evaluate lead acid battery lifespan in order to improve the final cost. In this case, batteries replacement dates are not fixed a priori and and consequently better optimization results are carried out.

INTRODUCTION

- Our research work has relevant contributions such as:

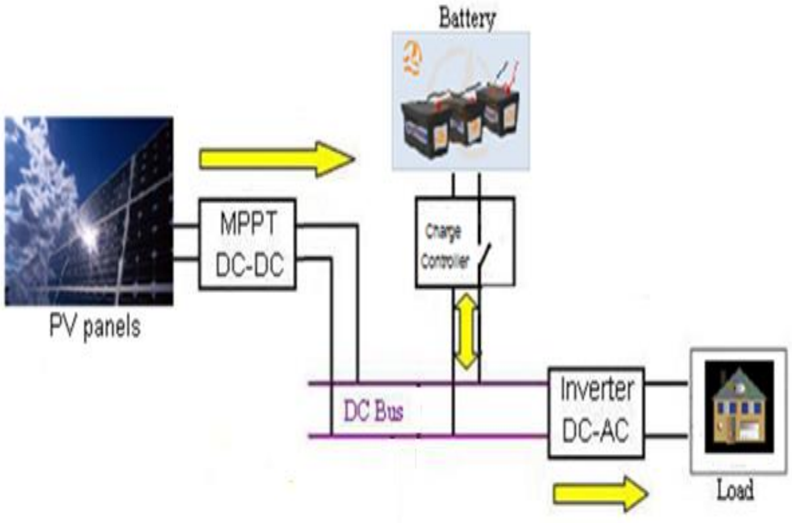
Batteries lifespan is considered at the design phase dynamically during optimization procedure. This approach is new for designing equipment or systems. Replacement time is deduced automatically and integrated to Life Cycle Cost (LCC). Replacement dates are not fixed a priori.

A detailed model that considers inclination of PV panels has been developed and integrated to our Matlab/Simulink dynamic simulator. This model is used to optimize panels' position. Such a tool is not common in literature especially with matlab/Simulink.

Batteries State Of Charge (SOC) limits SOCmin and SOCmax have been considered as optimization decision variables since batteries lifespan highly depends on the Depth Of Discharge (DOD) in order to justify their choice without aggressing the battery.

STANDALONE PHOTOVOLTAIC SYSTEM

Standalone photovoltaic system is mostly composed of two power sources: photovoltaic generator and batteries with charge controller.

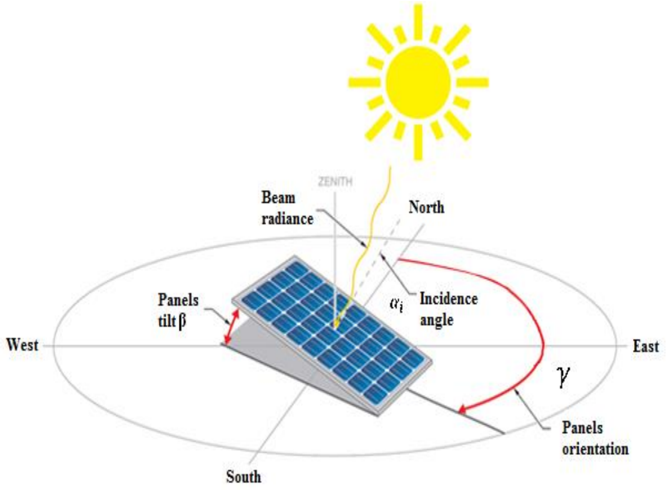


Schematic diagram of a standalone photovoltaic system with storage capabilities

Photovoltaic power

$$Ppv = \eta pv \times Apv \times Ir$$

$$\boldsymbol{Ir = Gb \times Rb + Gd \times \left(\frac{1+cos\beta}{2}\right) + Gh \times r \times \left(\frac{1-cos\beta}{2}\right)}$$



Photovoltaic power

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$$\boldsymbol{Ir = Gb \times Rb + Gd \times \left(\frac{1+cos\beta}{2}\right) + Gh \times r \times \left(\frac{1-cos\beta}{2}\right)}$$

Gb: beam irradiance on a horizontal plane;

Rb: shape factor. It's the ratio between direct irradiance received by panels in comparison with a horizontal plane, expressed by:

$$R_b = \frac{\cos \alpha_i}{\cos \theta}$$

Where α_i and θ are respectively the incidence angle on the panel and the solar zenith angle:

$$\cos \alpha_i = \cos \theta * \cos \beta + \sin \beta * \sin \theta * \cos(\emptyset - \gamma)$$

θ is limited to 89 ° angle from which irradiance is practically zero after sunset.

β: tilt angle of the collector surface.

γ: panel orientation (degrees): 180 ° corresponds to South direction.

∅: solar azimuth.

Gd: diffuse irradiance on a horizontal plane.

Gh: global irradiance on a horizontal plane. It corresponds to the irradiance measured by pyrometer.

r: represents the diffuse reflectance of the soil (also called ground albedo). It is set to 0.2 if the monthly average temperature is above 0°C.

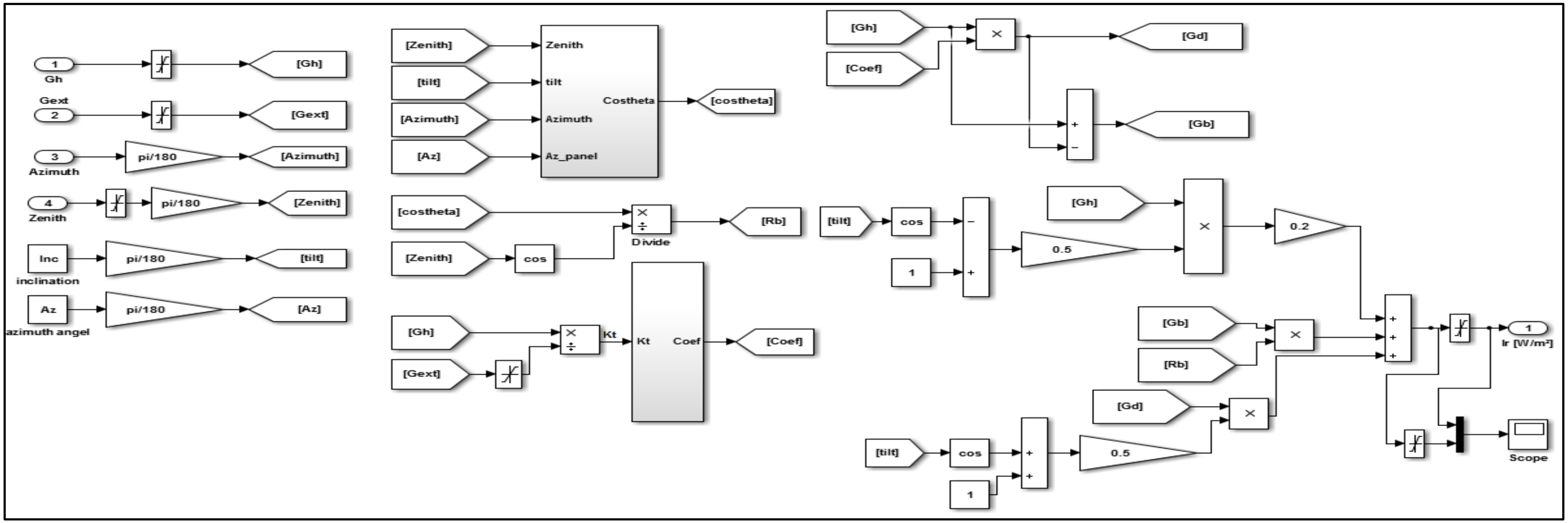
STANDALONE PHOTOVOLTAIC SYSTEM

Photovoltaic power

$$Ppv = \eta pv \times Apv \times Ir$$

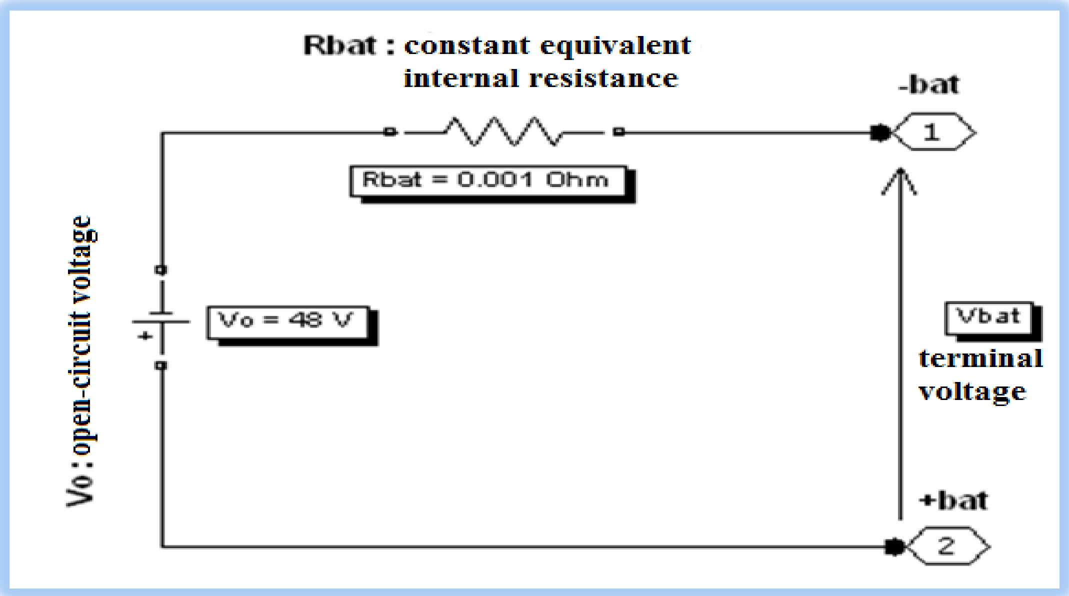
$$\boldsymbol{Ir = Gb \times Rb + Gd \times \left(\frac{1+cos\beta}{2}\right) + Gh \times r \times \left(\frac{1-cos\beta}{2}\right)}$$

Thus, using the global horizontal irradiances: measured *Gh* and extraterrestrial G_0 and sun position data, we have developed a Matlab/Simulink module to calculate the various components of the irradiance Ir incident on tilted panels with any inclination and any orientation. This module is added as a new subsystem to our hybrid power simulator previously developed. With this module, optimization of panels' inclination and orientation is considered for better reliability system, underlining the focus of this paper.



STANDALONE PHOTOVOLTAIC SYSTEM

Battery storage model



Ideal Lead-acid battery model

Battery aging model

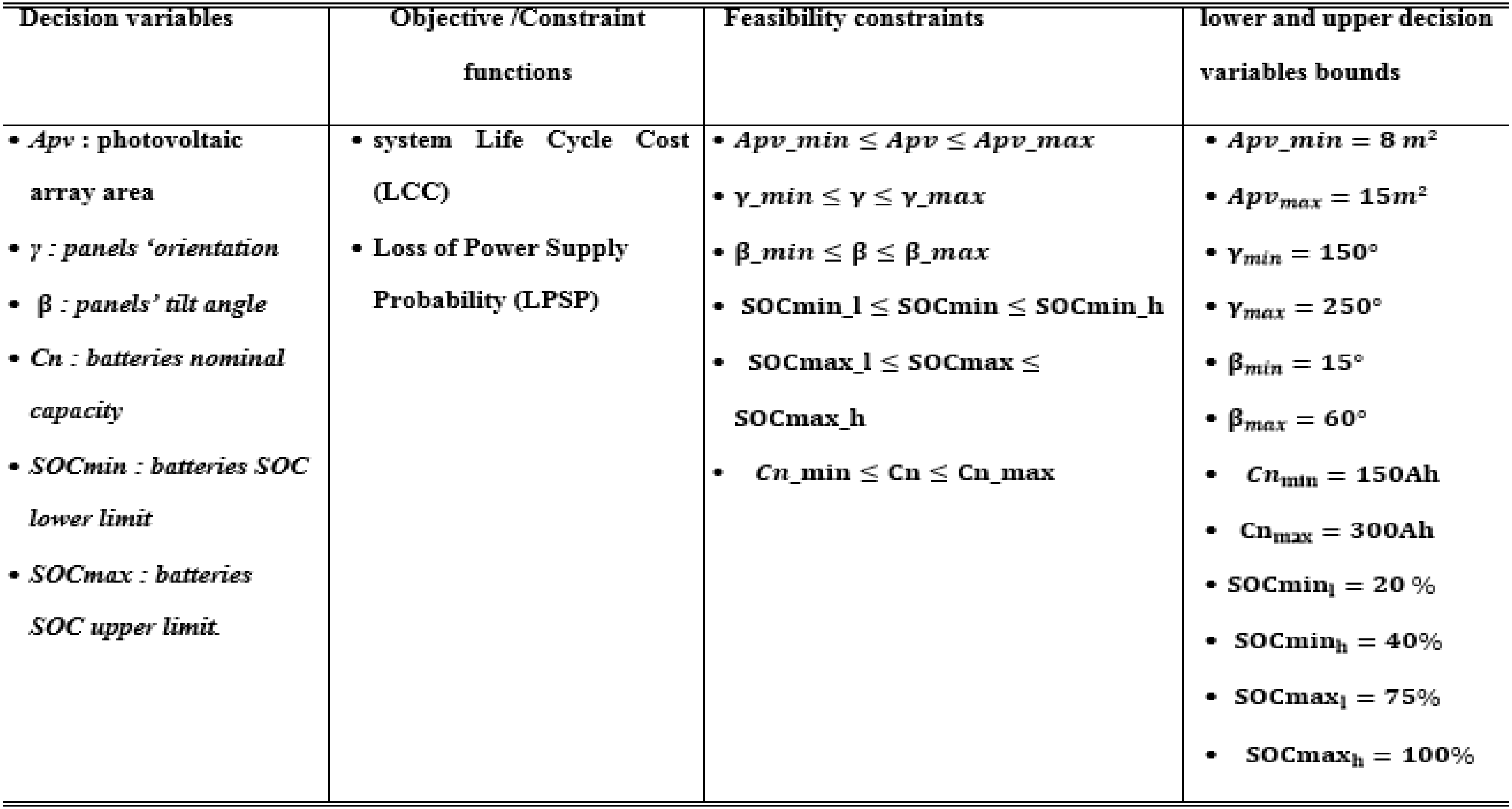
$$\boldsymbol{SOH(t)=\frac{Cn(t)}{Cn(t_0)}}$$

$$\mathbf{Cn(t)=Cn(t-\Delta t)-Cn(t_0)\times\delta_x\times\left(SOC(t-\Delta t)-SOC(t)\right)}$$

With δ_x the capacity loss coefficient depending on battery technology and Δt the simulation time step. We consider $\delta_{\mathrm{Plomb-tu}} = -0{,}05\%/\mathrm{EFC}$ for tubular lead-acid batteries.

DESIGN OPTIMIZATION PROCEDURE

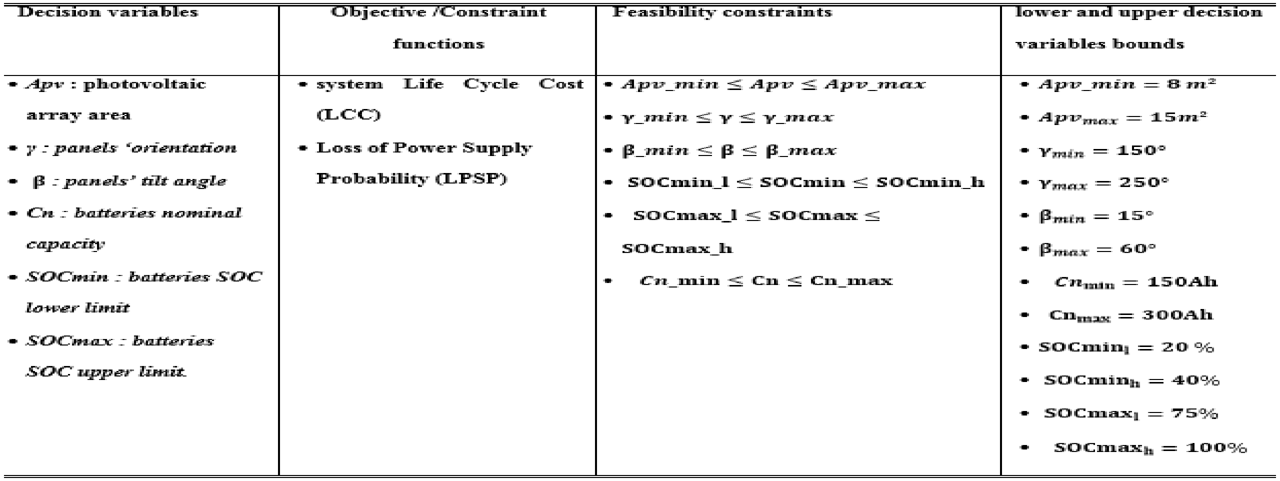
Objectives: design and evaluation criteria



Decision variables	Objective /Constraint functions	Feasibility constraints	lower and upper decision variables bounds
• *Apv* : photovoltaic array area • *γ : panels 'orientation* • *β : panels' tilt angle* • *Cn : batteries nominal capacity* • *SOCmin : batteries SOC lower limit* • *SOCmax : batteries SOC upper limit.*	• system Life Cycle Cost (LCC) • Loss of Power Supply Probability (LPSP)	• $Apv\_min \le Apv \le Apv\_max$ • $\gamma\_min \le \gamma \le \gamma\_max$ • $\beta\_min \le \beta \le \beta\_max$ • $SOCmin\_l \le SOCmin \le SOCmin\_h$ • $SOCmax\_l \le SOCmax \le SOCmax\_h$ • $Cn\_min \le Cn \le Cn\_max$	• $Apv\_min = 8\ m^2$ • $Apv_{max} = 15m^2$ • $\gamma_{min} = 150°$ • $\gamma_{max} = 250°$ • $\beta_{min} = 15°$ • $\beta_{max} = 60°$ • $Cn_{min} = 150Ah$ • $Cn_{max} = 300Ah$ • $SOCmin_l = 20\ \%$ • $SOCmin_h = 40\%$ • $SOCmax_l = 75\%$ • $SOCmax_h = 100\%$

DESIGN OPTIMIZATION PROCEDURE

Objectives: design and evaluation criteria



Decision variables	Objective /Constraint functions	Feasibility constraints	lower and upper decision variables bounds
- Apv : photovoltaic array area - γ : *panels 'orientation* - β : *panels' tilt angle* - Cn : *batteries nominal capacity* - *SOCmin : batteries SOC lower limit* - *SOCmax : batteries SOC upper limit*	- system Life Cycle Cost (LCC) - Loss of Power Supply Probability (LPSP)	- $Apv\_min \leq Apv \leq Apv\_max$ - $\gamma\_min \leq \gamma \leq \gamma\_max$ - $\beta\_min \leq \beta \leq \beta\_max$ - $\mathrm{SOCmin\_l} \leq \mathrm{SOCmin} \leq \mathrm{SOCmin\_h}$ - $\mathrm{SOCmax\_l} \leq \mathrm{SOCmax} \leq \mathrm{SOCmax\_h}$ - $Cn\_\mathrm{min} \leq \mathrm{Cn} \leq \mathrm{Cn\_max}$	- $Apv\_min = 8\ m^2$ - $Apv_{max} = 15m^2$ - $\gamma_{min} = 150°$ - $\gamma_{max} = 250°$ - $\beta_{min} = 15°$ - $\beta_{max} = 60°$ - $Cn_{\mathrm{min}} = 150\mathrm{Ah}$ - $\mathrm{Cn_{max}} = 300\mathrm{Ah}$ - $\mathrm{SOCmin_l} = 20\ \%$ - $\mathrm{SOCmin_h} = 40\%$ - $\mathrm{SOCmax_l} = 75\%$ - $\mathrm{SOCmax_h} = 100\%$

1) Cost considerations: minimizing Life Cycle Cost (LCC) of the system

$$\mathrm{LCC}[€] = PV_{LCC}[€] + Bat_{LCC}[€] = (650 \times Apv) + 4 \times \left(3 \times \left(1 + \sum_{i=1}^{Nbre\ of\ replacements} 0.95^{replacement\_year}\right)\right) \times \mathrm{Cn}$$

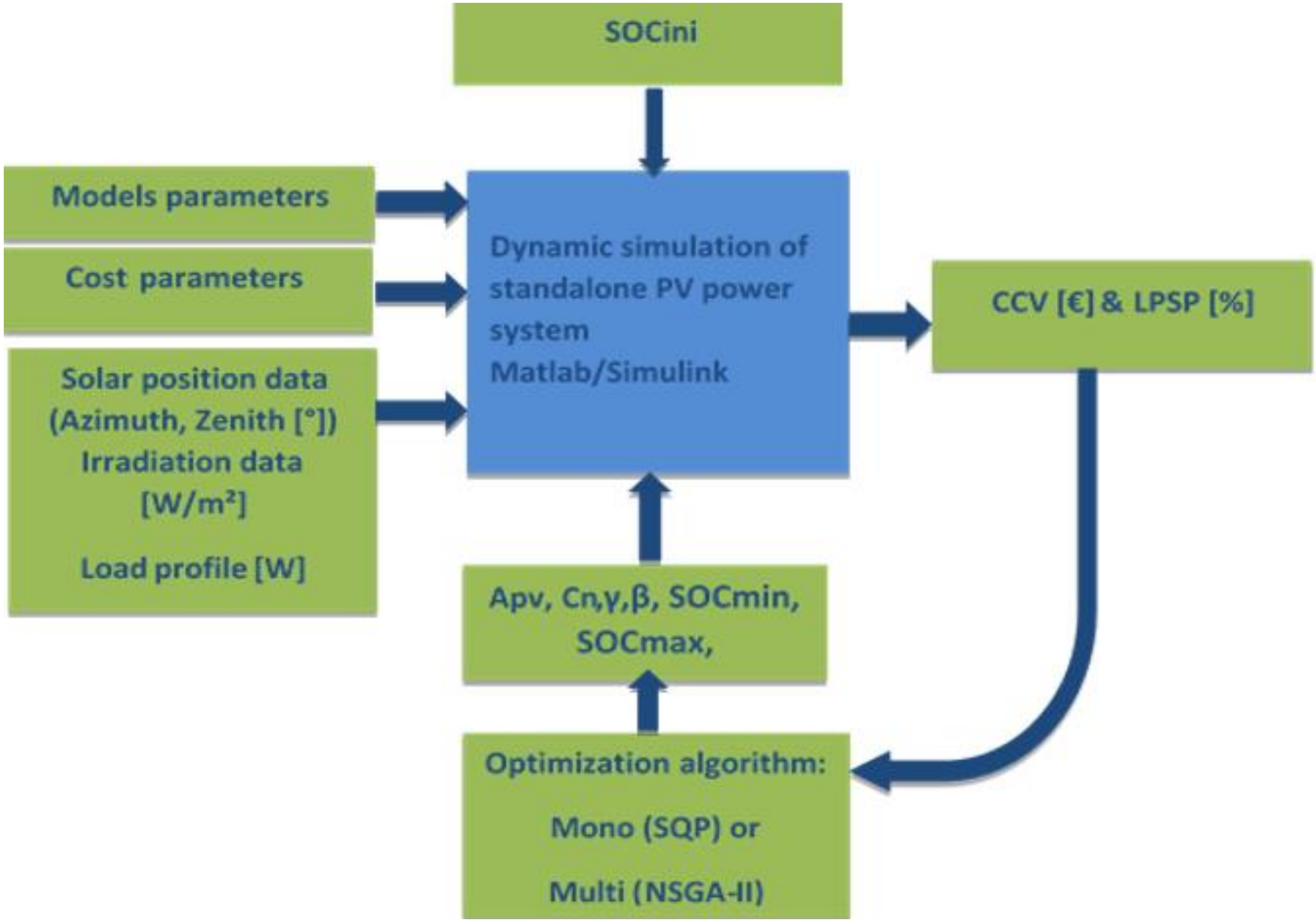
2) Reliability requirements: minimizing Loss of Power Supply Probability (LPSP)

$$\mathrm{LPSP}[\%]\ :\ \mathrm{Pr}\{\mathrm{Ppv} \leq \mathrm{Pdemand\ et\ SOC(t)} \leq \mathrm{SOCmin}\ \}$$

$$\mathrm{LPSP}(\Delta \mathrm{t}, \mathrm{Apv}, \beta, \gamma, \mathrm{Cn}, \mathrm{SOCmin}, \mathrm{SOCmax}) = \frac{\sum_{\mathrm{t}=1}^{\mathrm{T}} \mathrm{DE}(\mathrm{t}, \mathrm{Apv}, \beta, \gamma, \mathrm{Cn}, \mathrm{SOCmin}) \times \Delta \mathrm{t}}{\sum_{\mathrm{t}=1}^{\mathrm{T}} \mathrm{Pload}(\mathrm{t}) \times \Delta \mathrm{t}}$$

DESIGN OPTIMIZATION PROCEDURE

Computational method and algorithm



SOCini

Models parameters

Cost parameters

Solar position data (Azimuth, Zenith [°])
Irradiation data [W/m²]

Load profile [W]

Dynamic simulation of standalone PV power system
Matlab/Simulink

CCV [€] & LPSP [%]

Apv, Cn,γ,β, SOCmin, SOCmax,

Optimization algorithm:

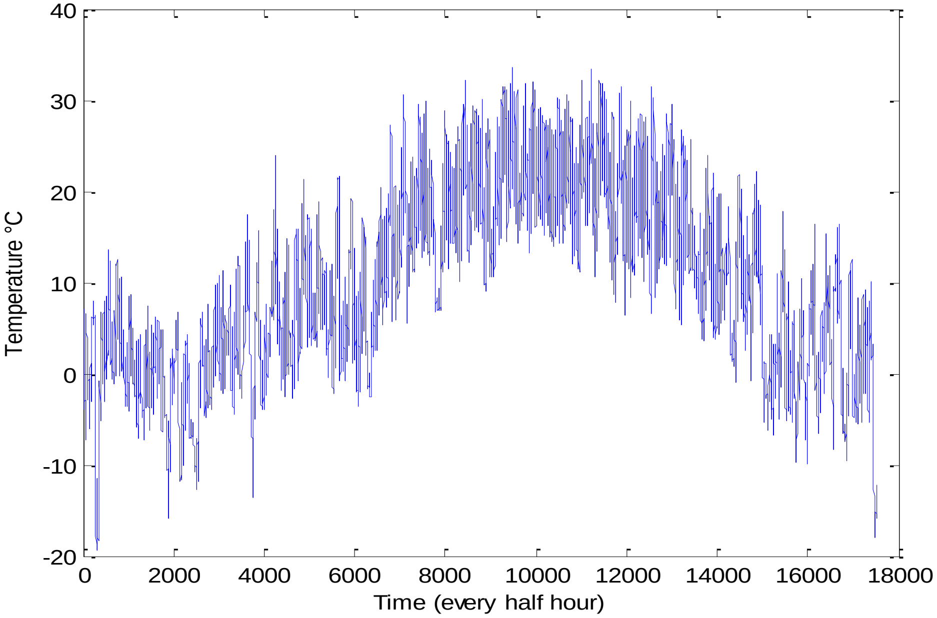
Mono (SQP) or

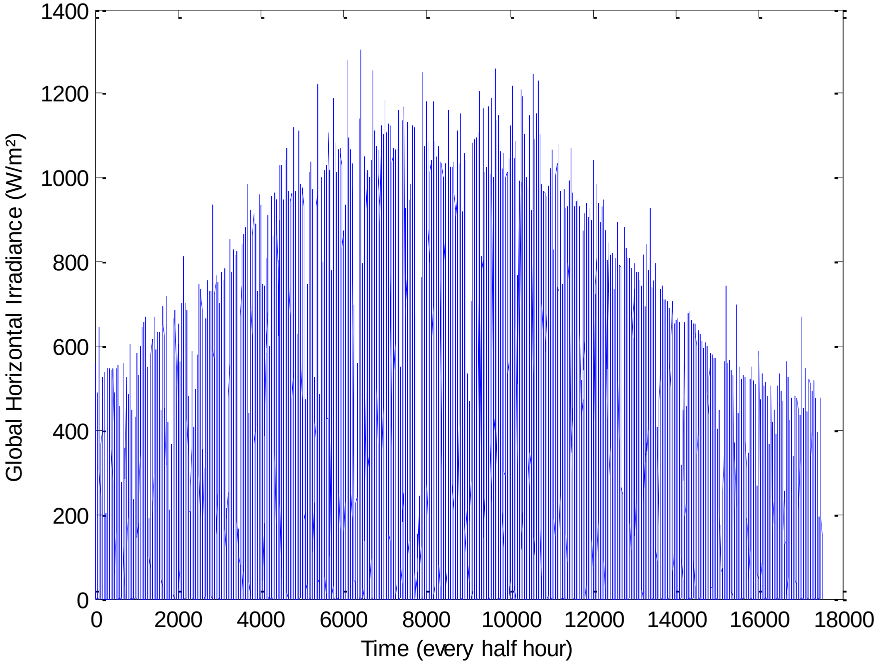
Multi (NSGA-II)

RESULTS AND DISCUSSIONS

Case study

Half hourly solar radiance and temperature were acquired from the National Wind Technology Centre- Colorado (Latitude: 39° North, Longitude: 105° West, Elevation: 1855 meters) web site for the year 2010 with a low photovoltaic potential **[1857,5 KWh/year/m^2 Mean : 189 W/m^2]**

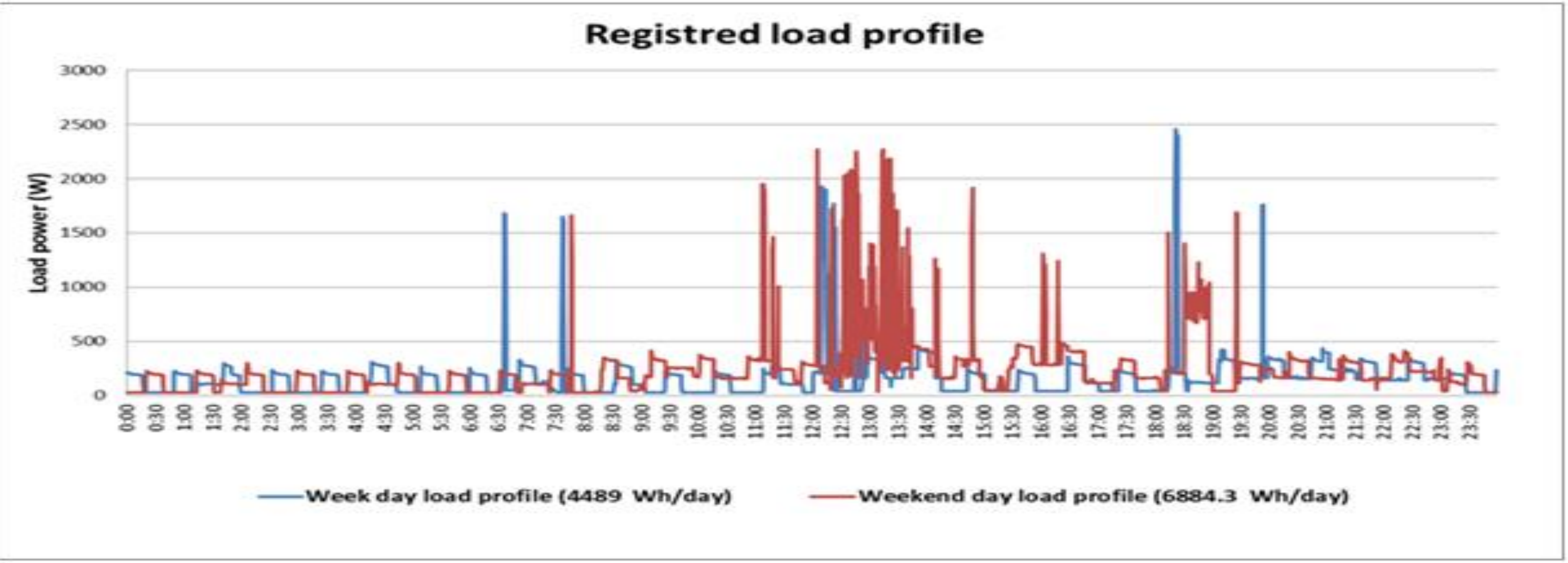




RESULTS AND DISCUSSIONS

Case study

Half-hourly load profile



These profiles were extrapolated for the full year 2010 considering seasonal variations of the electric charge/load and applying correction factors. Thereby, annual electricity consumption of the residence is estimated at **2178 kWh/year in 2010 [Min: 27.6 KW; Max: 3796.3 KW; Mean: 250.5 KW].**

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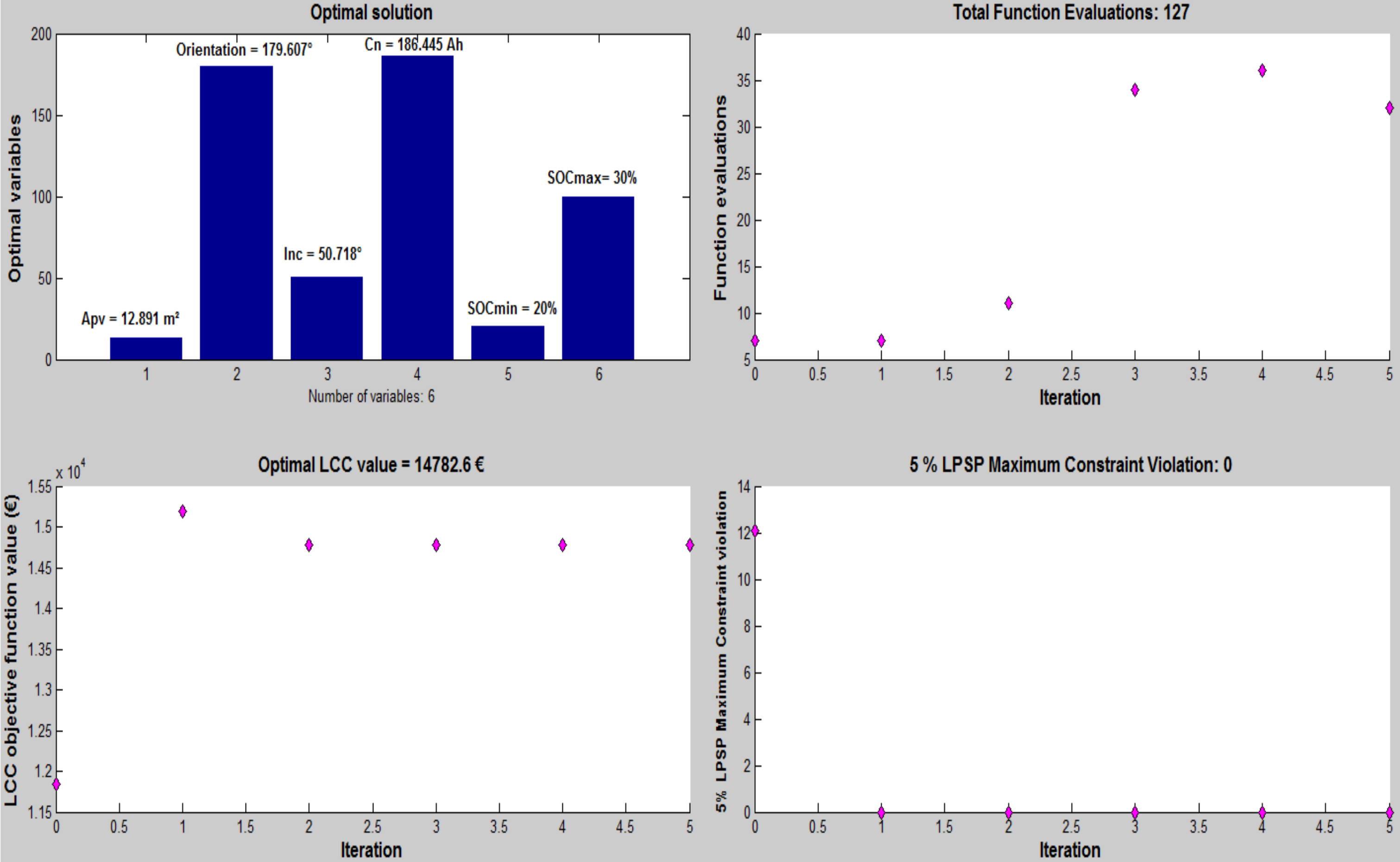
EIGSI ÉCOLE D'INGÉNIEURS LA ROCHELLE
EIGSICA Ecole d'Ingénierie en Génie des Systèmes Industriels Casablanca
LIAS
L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

RESULTS AND DISCUSSIONS

Case study

SQP non-linear programming optimization results



RESULTS AND DISCUSSIONS

Case study

SQP non-linear programming optimization results

The design configuration of the PV system that satisfies maximum 5 % LPSP criterion with a small cost is obtained for:

- Photovoltaic modules’ installed area Apv = 13 m^2, eight CHSM 6610P-235 235W panels for instance can be installed.
- Panels’ inclination $\beta=51^{\circ}$ and orientation $\gamma=180^{\circ}$, nearly.
- Battery bank storage capacity gives Cn = 186.5 Ah. Four Deep Cycle OutBack Power EnergyCell RE200 12V 200Ah Batteries can be installed in series.
- Battery management bounders: SOCmin=20 % and SOCmax=100%. Now, a justified choice.

With this solution, we expect a cost of about 14782.6 € and a batteries’ lifespan of nearly 5.3 years (DR per year = 5.633%), means four batteries replacements in 25 years.

Optimization procedure favorites deep batteries cycling (DOD=80%) in order to reduce batteries cost especially that a variation of 20% on DOD implies a little variation of DR when system is well designed.

CONCLUSION AND PERSPECTIVES

This methodology will help designers or installers, advanced users in general. In short or medium term, a tool aid decision could be developed for basic users in order to simplify the process of selection between different criteria.

Thank you for your attention!

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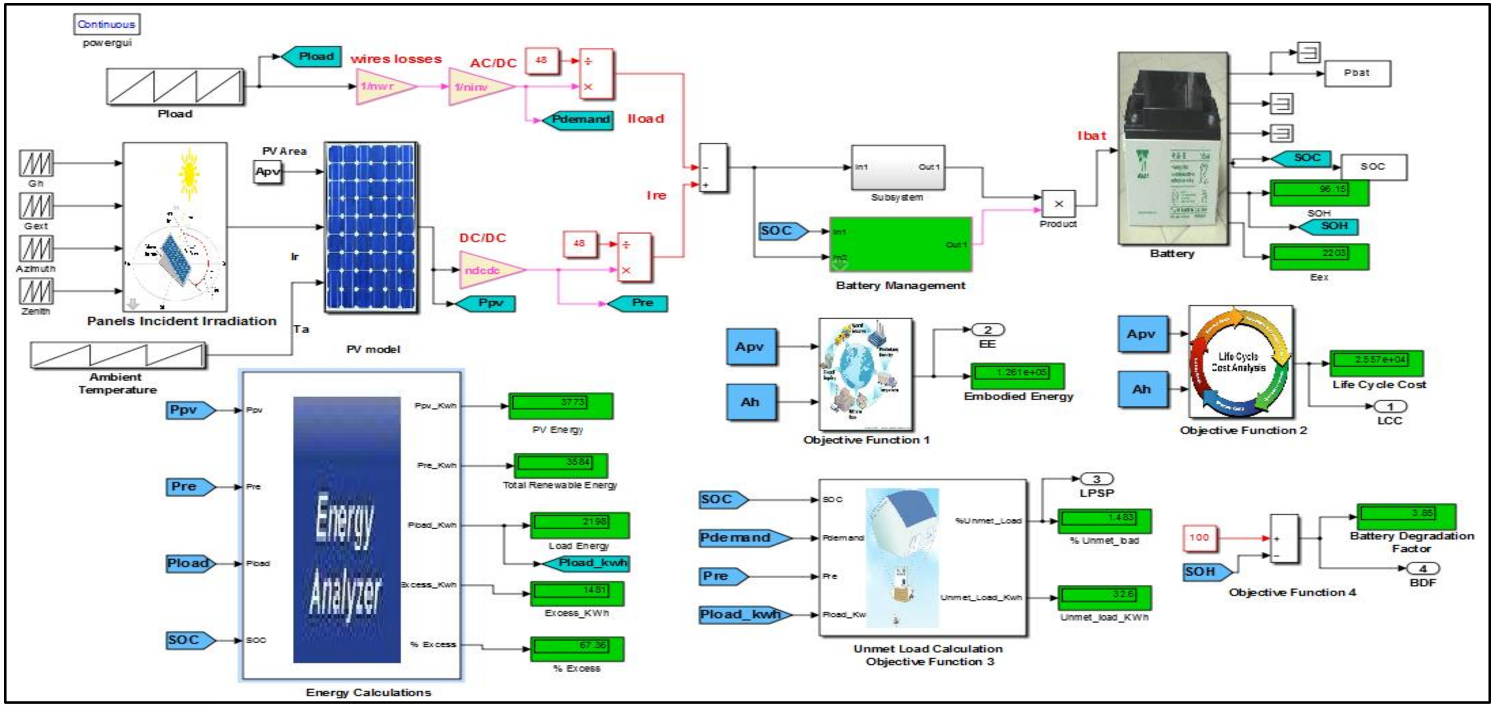

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