# Optimization of n-PERT Solar Cell under Atacama Desert Solar Spectrum

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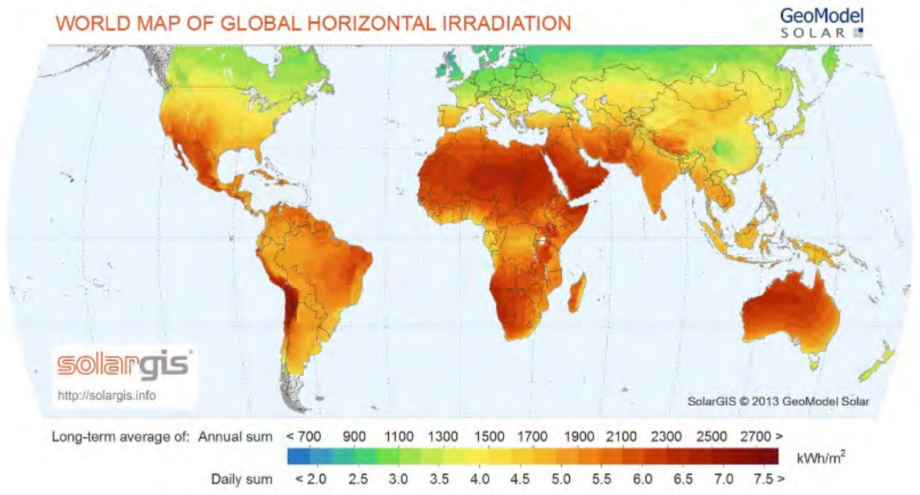
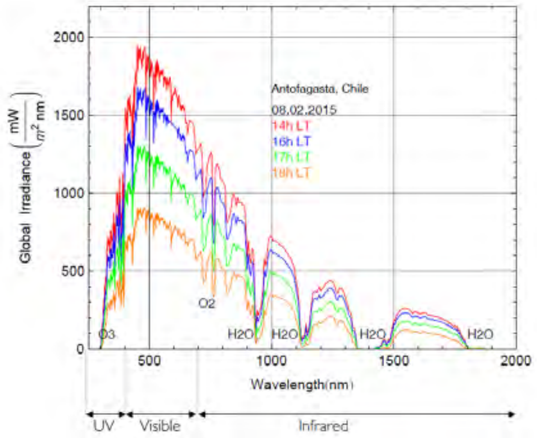
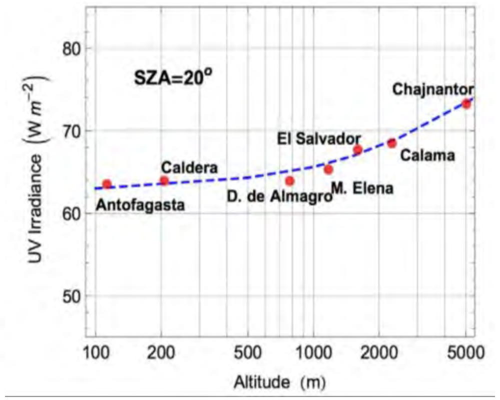
Master's Degree in Numerical Simulation in Science and Engineering with COMSOL Multiphysics

# Introduction: Solar resource in the world



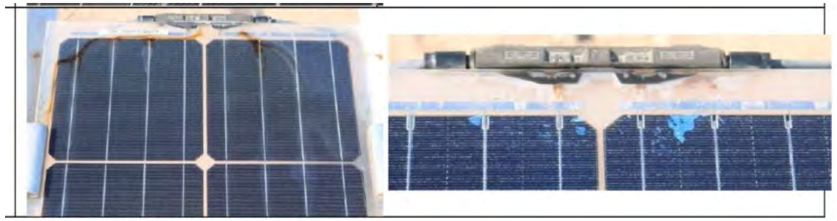




**T**ot. **O**zone **C**olumn
**A**erosol **O**pt. **D**epth
**P**recipitable **W**ater
**O**ptical **P**ath **L**ength

- 5.6% of Reference Spectrum (AM1.5G) is UVA + UVB.
- Atacama Desert receives the highest irradiation in the world, with 7.7% of its energy in the UV range.

Annual dose of UV-B is **35-65% higher in Atacama** than in the south of EU → Degradation

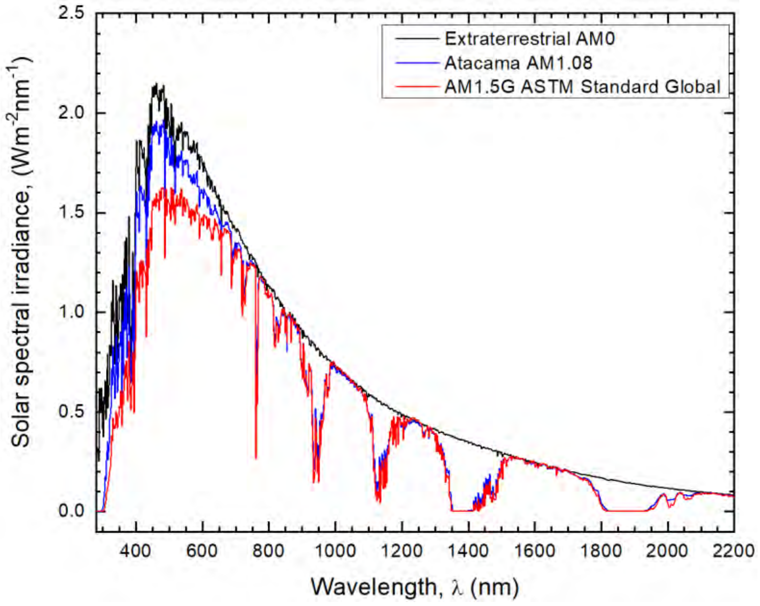


Solar Energy Materials & Solar Cells 236 (2022) 111508

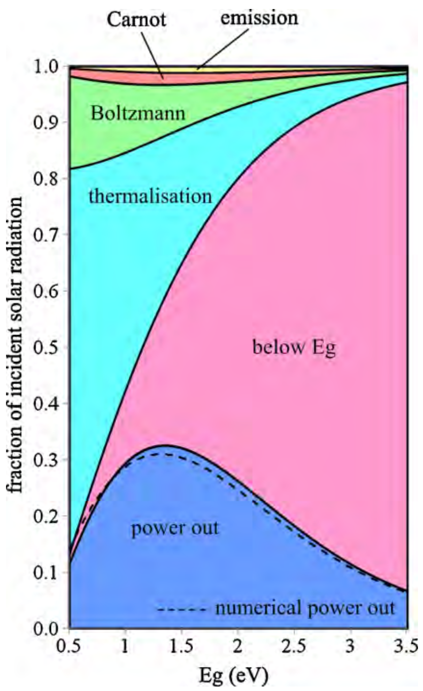
Marzo et al. Standard or local solar spectrum? Implications for solar technologies studies in the Atacama desert. Renewable Energy 127 (2018), 871-882
Cordero et al. *The Solar Spectrum of Atacama Desert*. Scientific Reports 6, Article number: 22457 (2016).
Cordero et al. "*Ultraviolet radiation in the Atacama Desert*". Antonie Van Leeuwenhoek. 2018;111(8):1301-1313.

# Problem description

- There are differences with respect to reference spectrum: intensity and UV content.
  - → Desert Label for Atacama Desert
- Solar cell is designed for high efficiency under standard testing conditions (STC).
  - → AM1.5G spectrum, 1000 W/m$^2$ and 25 °C.
- The PV device exhibits losses when operating at non-standard conditions (no optimum).




A Marzo, P Ferrada "*Standard or Local Solar Spectrum? Implications for Solar Technologies Studies in Atacama Desert*". Ren. En. 127 (2018), 871.

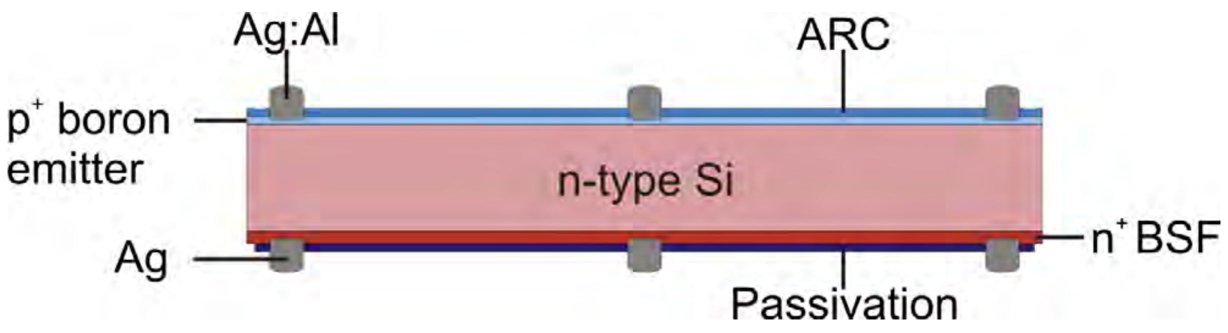



L. C. Hirst, N. J. Ekins-Daukes. *Fundamental losses in solar cells*. Prog. Photovolt: Res. Appl. 2011; 19:286–293.

F. Lelievre,…,A. Marzo, P. Ferrada et al. *Desert label development for improved reliability and durability of PV modules in harsh desert conditions*. Solar Energy Materials & Solar Cells 236 (2022) 111508.

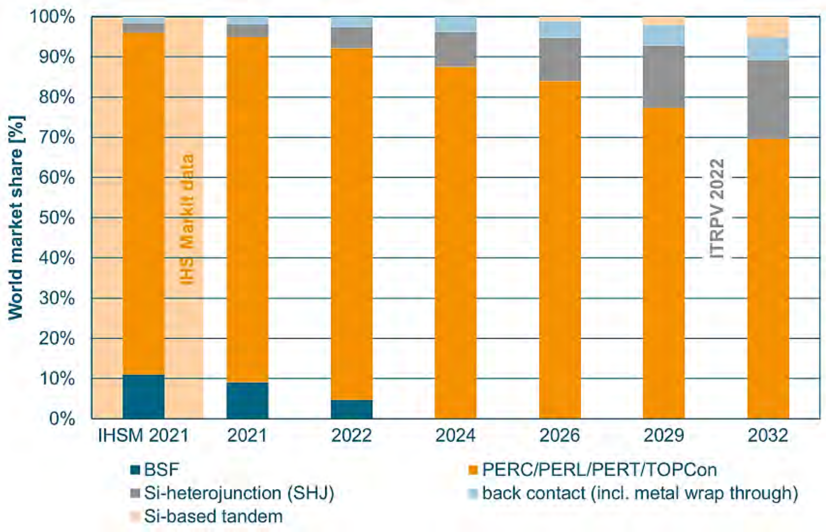
# Objectives

- To determine optimal parameters of a n-PERT cell when operating under Atacama Desert spectral conditions.
- To compute the characteristic curve of an optimized n-PERT cell for a whole day in Atacama Desert.




n-PERT

**n**-type **p**assivated **e**mitter and **r**ear **t**otally diffused




**P. Ferrada, A. Marzo et al. “*Potential for photogenerated current for Si based PV modules in the Atacama Desert*”, Solar Energy 144 (2017), 580-593.**

**International Technology Roadmap of Photovoltaics (ITRPV) 2022.**

# Materials & methods: Stages

1. Validation

   1.1 Fabricate a standard n-PERT solar cell.

   1.2 Model/simulate the n-PERT under AM1.5G.

   -Mesh Independence study

   1.3 Explain differences and improve the model.

2. Optimization

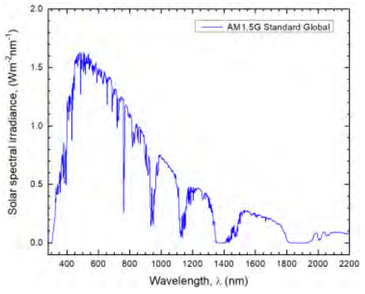
   2.1 Define *obj func*, *control par*, *const* and *output var*.

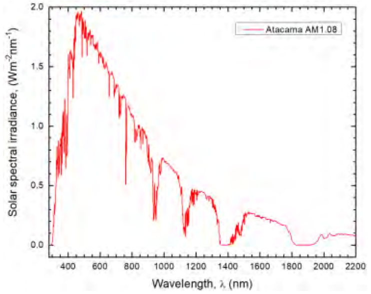
   2.2 Configure COMSOL + MATLAB for optimization.

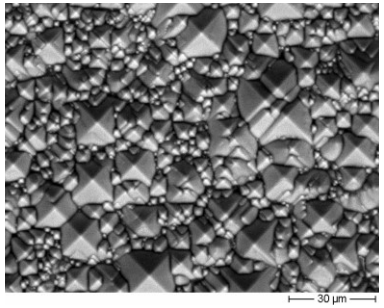
3. Prediction

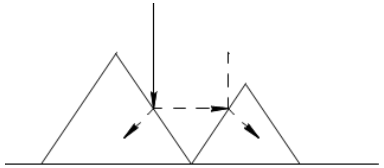
   3.1 Use fixed and optimized inputs in the model.

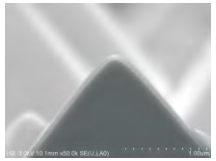
   3.2 Calculate the JV curve for a whole day in Atacama D.

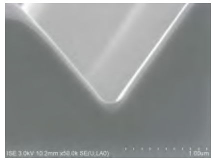


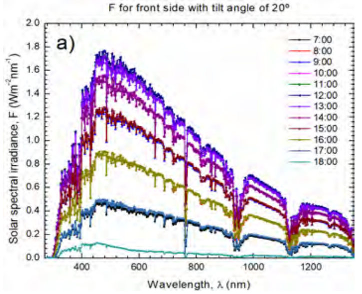


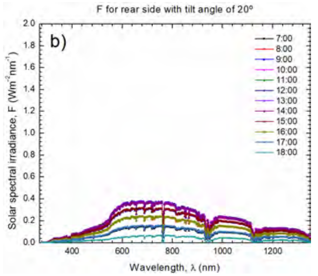


Higher Surface area:

→ Higher absorption and less reflection ($J_{sc,meas}$=1.17 $J_{sc,calc}$)

→ Higher recombination rate (1.7 times more)

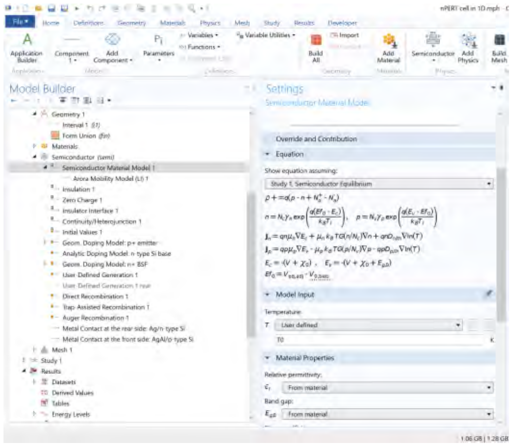


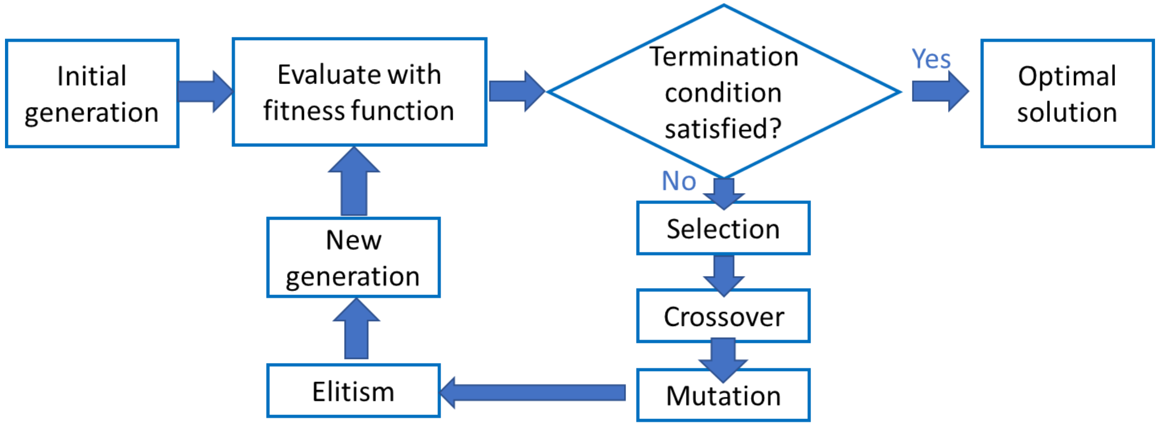

**A. Fell et al. *Input Parameters for the Simulation of Silicon Solar Cells in 2014*. IEEE Journal of PV 5 (2015), 1250–1263**

# Materials & methods: Model and optimization

- Model: COMSOL
  - Semiconductor Module
  - Geometry: 1D object
  - Material: c-Si
  - Stationary study
    - Parametric Sweep over voltage
  - Direct Solver: MUltifrontal Massively Parallel Solver (MUMPS)



- Optimization in MATLAB
  - Function nPERTopt(x) from COMSOL saved as *m
  - Genetic Algorithm (GA)
  - Script containing input parameters for the GA



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# Theory: Poisson, drift-diffusion, continuity

Poisson equation $\nabla \cdot (-\varepsilon_r \nabla V) = \rho$

Net charge $\rho = q(p - n + N_d^+ - N_a^-)$

Electron Conc. $n = N_C F_{1/2}\left(-\frac{E_c - E_{fn}}{k_B T}\right)$ $N_C = 2\left(\frac{m_e^* k_B T}{2\pi\hbar^2}\right)^{3/2}$

Hole Conc. $p = N_V F_{1/2}\left(-\frac{E_{fp} - E_v}{k_B T}\right)$ $N_V = 2\left(\frac{m_h^* k_B T}{2\pi\hbar^2}\right)^{3/2}$

Fermi Integral $F_{1/2}(\eta_c) = \int_0^{\infty} \frac{{\eta_c}^{1/2}}{1+e^{x-\eta_c}} dx$

| | |
|---|---|
| Relative permittivity of silicon | $\varepsilon_r$ |
| Charge density | $\rho$ [C/cm$^3$] |
| Electron, hole concentration | $n, p$ [cm$^{-3}$] |
| Ionized donor, acceptor impurity | $N_d^+, N_A^-$ [cm$^{-3}$] |
| Eff. Density of states in Cond. Band | $N_C$ [cm$^{-3}$] |
| Eff. Density of states in Val. Band | $N_V$ [cm$^{-3}$] |
| Quasi Fermi levels | $E_{fn}, E_{fp}$ [eV] |
| Equilibrium Fermi Level | $E_{f0}$ [eV] |
| Temperature | $T$ [K] |

Doping $N = N_0 \exp((-d/l)^2)$

Decay length $l = d_j / \sqrt{ln([N_0/N_b])}$

**P. Altermatt. Models for numerical device simulations of crystalline silicon solar cells—a review. J Comput Electron (2011) 10:314–330.**

# Theory: Poisson, drift-diffusion, continuity

Transport for electrons (e) $\boldsymbol{J_n} = qn\mu_n(N_d^+, T)\boldsymbol{E} + \mu_n k_B T g\left(\frac{n}{N_C}\right)\nabla n + qnD_{n,th}\nabla \ln(T)$

Transport for holes (h) $\boldsymbol{J_p} = qp\mu_p(N_a^-, T)\boldsymbol{E} - \mu_p k_B T g\left(\frac{p}{N_V}\right)\nabla p - qpD_{p,th}\nabla \ln(T)$

Continuity for e and h $\frac{\partial n}{\partial t} = \frac{1}{q}(\nabla \cdot \boldsymbol{J_n}) - U_n$ $\frac{\partial p}{\partial t} = -\frac{1}{q}(\nabla \cdot \boldsymbol{J_p}) - U_p$

Net e, h Recombination $U_n = \sum R_{n,i} - \sum G_{n,i}$ $U_p = \sum R_{p,i} - \sum G_{p,i}$

Generation rate for e and h: $G(z) = \frac{4\pi}{hc}(1 - f_{met}) \int_{\lambda_1}^{\lambda_2} \kappa(\lambda)\, F(\lambda)\, e^{-\frac{4\pi\, \kappa\, z}{\lambda}}[1 - R(\lambda)]d\lambda$

Current density for e, h
$J_n, J_p$ [mA/cm$^2$]

Electron, hole mobility
$\mu_n, \mu_p$ [cm$^2$/(V s)]

Thermal diffusion coefficient
$D_{n,th}, D_{p,th}$ [cm$^2$/s]

Electric field
$\boldsymbol{E}$ [V/m]

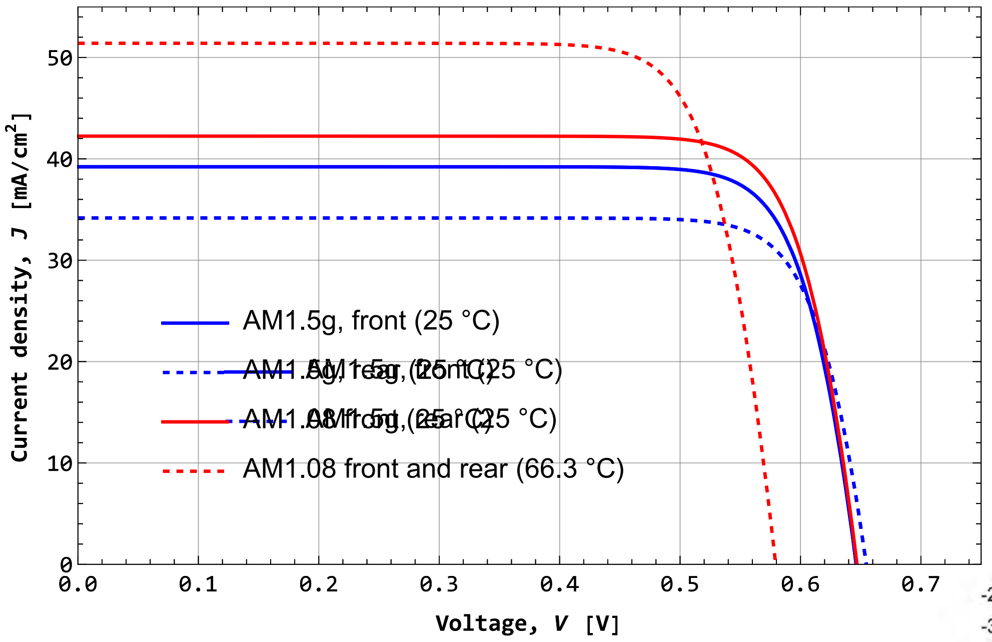
Recombination rate
$R_n, R_p$ [1/(cm$^3$ s]

Solar spectral irradiance
$F(\lambda)$ [W/(m$^2$ nm))]

Extinction coefficient
$\kappa$

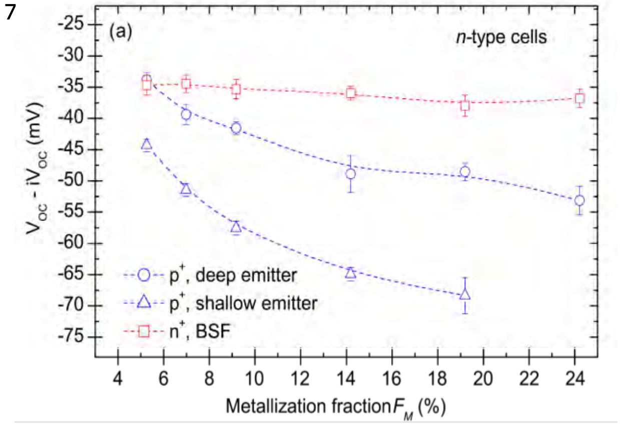
Spectral reflection
$R(\lambda)$

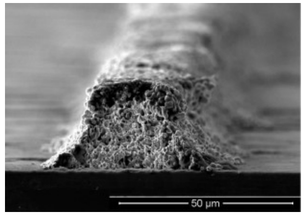
# Results & discussion : Validation




| | IV measurement | | IV simulation | | Relative difference (%) | |
|---|---|---|---|---|---|---|
| Parameter | Front side | Rear side | Front side | Rear side | Front side | Rear side |
| $J_{sc}$ (mA/cm$^2$) | 39.2 ± 0.03 | 34.6 ± 0.03 | 39.2 | 34.2 | 0.1 | 1.3 |
| $V_{oc}$ $(mV)$ | 653.1 ± 2 | 649.7 ± 2 | 646.4 | 654.6 | 1.0 | 0.8 |
| $P_{mpp}$ $(W)$ | 4.9 ± 0.02 | 4.3 ± 0.09 | 5.3 | 4.6 | 8.3 | 6.9 |
| $FF$ (%) | 78.3 ± 0.2 | 78.2 ± 0.16 | 78.7 | 78.7 | 0.5 | 0.6 |
| $\eta$ (%) | 20 ± 0.08 | 17.6 ± 0.1 | 20.0 | 18.0 | 0.3 | <0.1 |

- Variation in $f_{met}$
- Reduction in $V_{oc}$ for p$^+$-type emitter
  - 45 mV due to front metallization
  - 35 mV due to rear metallization
- $P_{mpp} = P_{mpp,0} - R_{ser} I_{mpp}{}^2$





**Edler et al. *Metallization-induced recombination losses of bifacial silicon solar cells*. Prog. Photovolt: Res. Appl. 2015; 23:620–627.**

**Correa. *Electrical conduction in the Ag/si interface of Si solar cells*. 9th International Conference on Low Dimensional Structures and Devices, 2-6 December 2019At: Puerto Varas, Chile.**

# Results & discussion: Optimization in MATLAB

Inputs of the Genetic Algorithm

[$d_E$, $d_{cell}$, $d_{BSF}$, $N_E$, $N_B$, $N_{BSF}$]

Maximum values (xmin): [0.2, 150, 0.2, 1e19, 1e14, 1e19]
Minimum values (xmax): [1, 200, 1, 1e20, 1e15, 5e20]

Population size (Npop): 70
Generation N° (Ngen): 110
Stop criterium (Nsic): 10
Mutation probability (pmut): 0.1
Refinement (resfin): 0

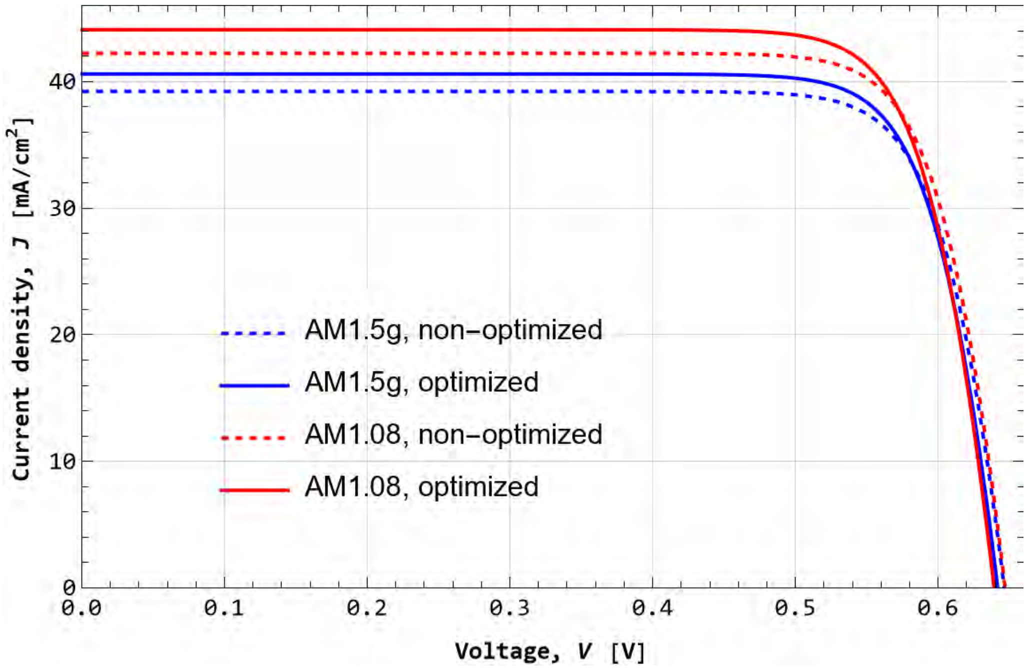
Function to minimize

```
P=-model.result.numerical('pev1').getReal;
```

| Description | Parameter | Initial values | AM1.5g | AM1.08 |
|---|---|---|---|---|
| Emitter thickness | $d_E$ (um) | 0.65 | 0.20 | 0.20 |
| Cell thickness | $d_{cell}$ (um) | 180 | 150 | 150 |
| BSF thickness | $d_{BSF}$ (um) | 0.45 | 0.33 | 0.25 |
| Emitter doping | $N_E$ ($cm^{-3}$) | $2.44\times10^{19}$ | $9.89\times10^{19}$ | $9.36\times10^{19}$ |
| Base doping | $N_B$ ($cm^{-3}$) | $8.44\times10^{14}$ | $9.83\times10^{14}$ | $9.84\times10^{14}$ |
| BSF doping | $N_{BSF}$ ($cm^{-3}$) | $6.16\times10^{19}$ | $3.87\times10^{20}$ | $4.12\times10^{20}$ |

# Results & discussion : Cell response, optimized to Atacama Spectrum

- JV of optimized solar cell to AM1.5g and AM1.08
- Table with the JV parameters
  - Optimized case
  - Non-optimized cell



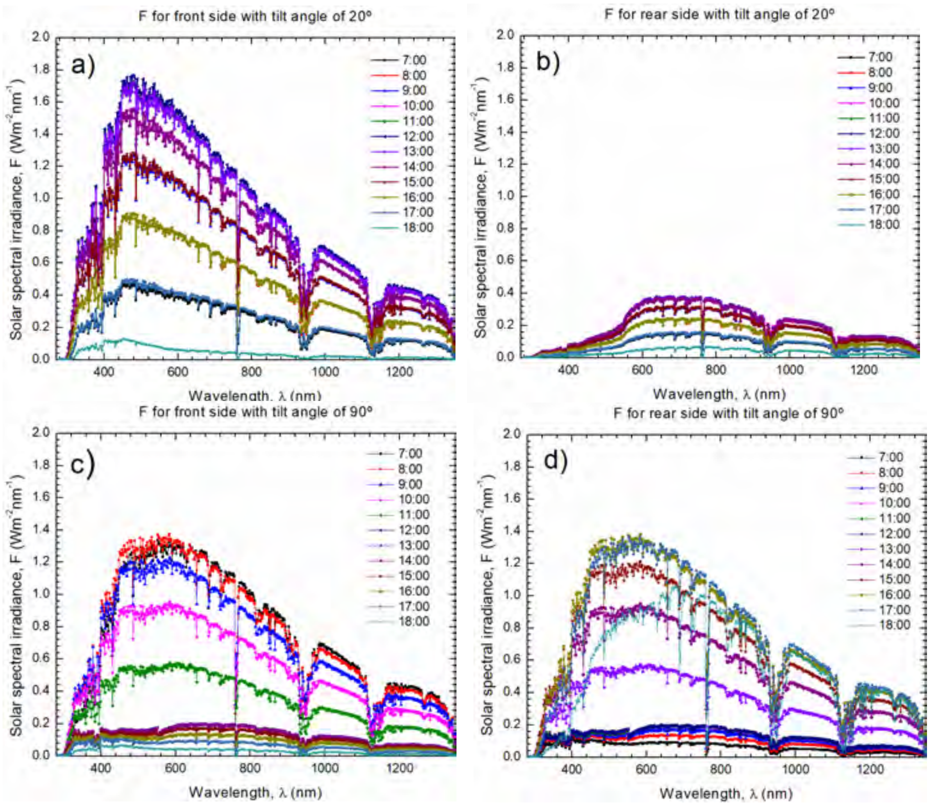

| | Optimized case | | | | |
|---|---|---|---|---|---|
| | $J_{sc}$ (mA/cm²) | $V_{oc}$ (mV) | $P_{mpp}$ (W) | FF (%) | Eta (%) |
| Standard AM1.5g | 40.6 | 641.7 | 5.5 | 82.3 | 21.5 |
| Atacama AM1.08 | 44.1 | 639.2 | 5.9 | 83.0 | 23.4 |

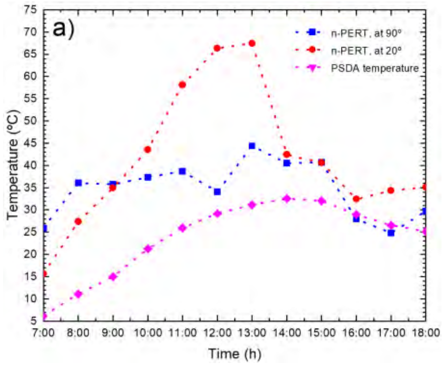
| | Non-optimized case | | | | |
|---|---|---|---|---|---|
| | $J_{sc}$ (mA/cm²) | $V_{oc}$ (mV) | $P_{mpp}$ (W) | FF (%) | Eta (%) |
| Standard AM1.5g | 39.2 | 646.4 | 5.3 | 78.7 | 20.0 |
| Atacama AM1.08 | 42.2 | 647.0 | 5.7 | 78.9 | 21.6 |

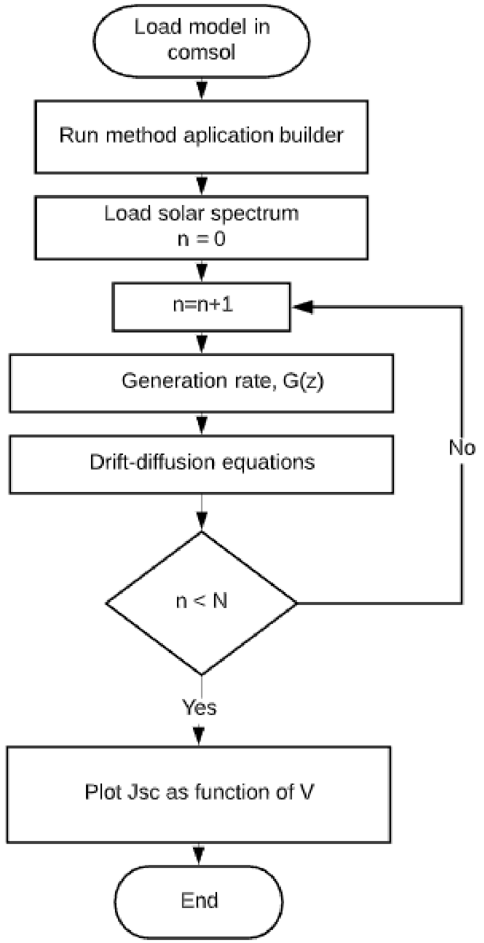
| | Comparison though the relative difference | | | | |
|---|---|---|---|---|---|
| | $J_{sc}$ | $V_{oc}$ | $P_{mpp}$ | FF | Eta |
| Standard AM1.5g | 3.6% | -0.7% | 4.3% | 4.6% | 7.6% |
| Atacama AM1.08 | 4.3% | -1.2% | 4.7% | 5.2% | 8.5% |

$$100\,(X_{opt} - X_{non\text{-}opt}) / X_{non\text{-}opt}$$

# Results & discussion : Java



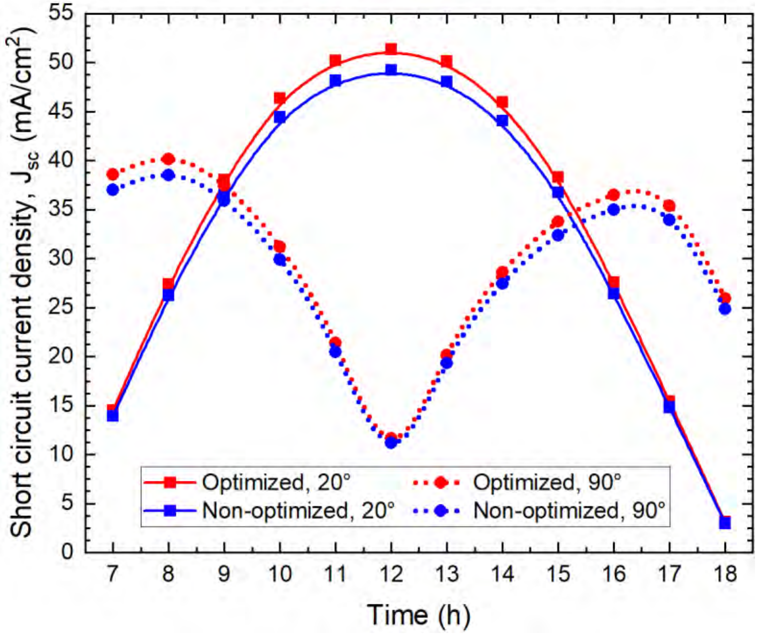



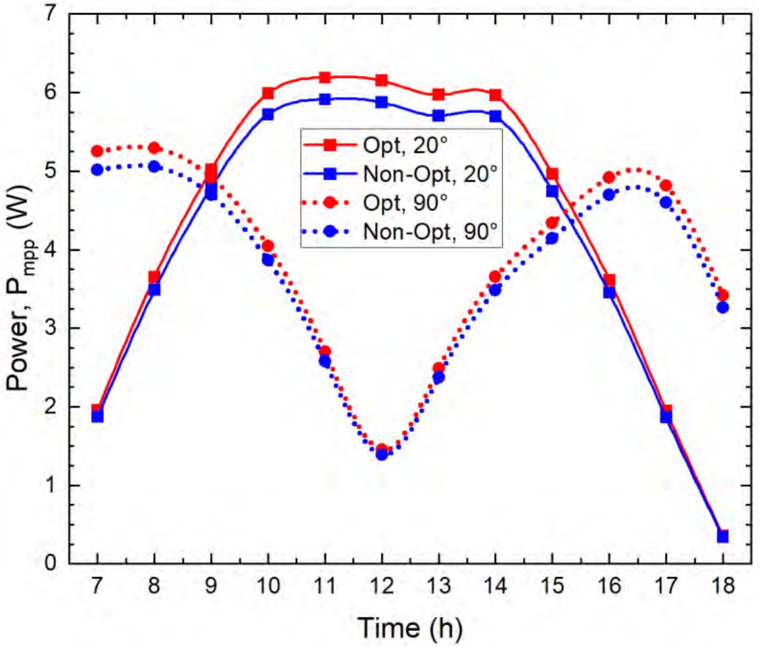

$$G(z) = \frac{4\pi}{hc}\left(1 - f_{m,f}\right)\int_{\lambda_1}^{\lambda_2} \kappa(\lambda)\, F_f(\lambda)\, e^{-\frac{4\pi\,\kappa\, z}{\lambda}}\left[1 - R_f(\lambda)\right]d\lambda + \frac{4\pi}{hc}\left(1 - f_{m,r}\right)\int_{\lambda_1}^{\lambda_2} \kappa(\lambda)\, F_r(\lambda)\, e^{-\frac{4\pi\,\kappa\, z}{\lambda}}\left[1 - R_r(\lambda)\right]d\lambda$$

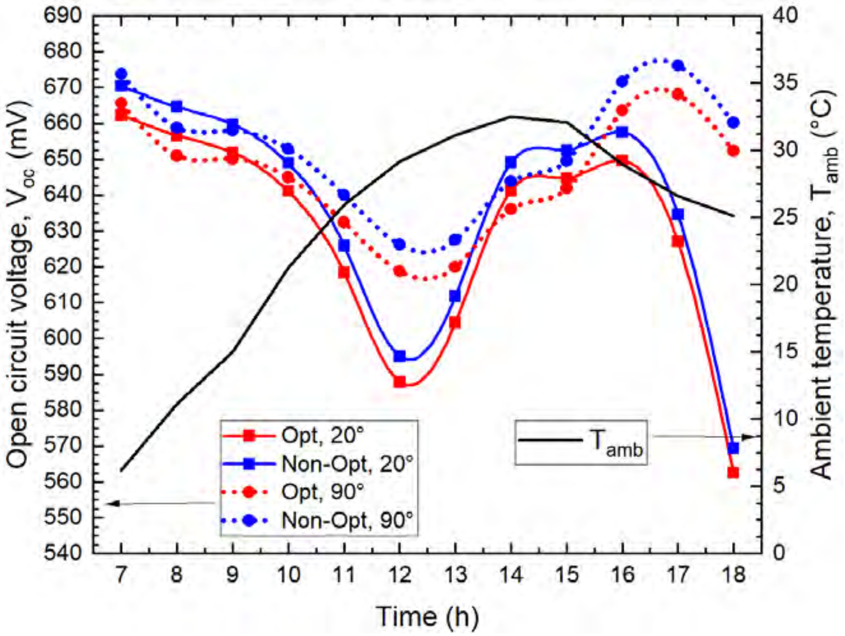
**A. Fell et al. *Simplified Device Simulation of Silicon Solar Cells Using a Lumped Parameter Optical Model*. Journal of Photovoltaics 6:3 (2016), 611-616.**

**M. M. Chowdhury. *Approximation of Carrier Generation Rate in Common Solar Cells and Studies for Optimization of n⁺p Silicon Solar Cell for AM1.5G and AM1.5D*. 2012 7th Int. Conf. on Electrical and Computer Engineering 20-22 December 2012, Dhaka, Bangladesh.**

# Results & discussion : Response for different spectra along the day



# Conclusions and outlook

- The solar cell model is valid for a family of cases
  - Cell structure: $p^+nn^+$
  - Monofacial and bifacial case
  - For any illumination; only front, only rear or simultaneous
- The model combined with MATLAB allowed to optimize the device under a representative Atacama Spectrum
  - Thickness and doping level of the emitter, cell (base), back surface field
- The model combined with Java allowed to predict the performance for a whole day in Atacama Desert
  - Automation of calculations and less time consumption
- Application to PV module response, provided that absorption of c-Si is known

# Thanks for your attention

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