The OTSun WebApp

-Tutorial 2-

First edition

Simulation of a Silicon Solar Cell

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1. Objectives and first steps

In this tutorial, an example of a simulation with the OTSun WebApp is outlined step by step. The main goal of this tutorial is to demonstrate how to obtain the optical efficiency of a silicon solar cell.

The silicon solar cell, illustrated in Fig. 1, consists of a glass layer covered with an anti-reflective (AR) coating, an encapsulation layer (EVA), another anti-reflective coating, the photovoltaic material, and finally the substrate that is used as an electrical conductor (see Fig. 2).

The dimensions of this solar cell are not realistic, but have been considered as a square of 1000 mm per side to minimize the edge effects. Furthermore, for the sake of simplicity, the front contacts are not taken into account.

Before conducting the simulation, it is recommended that the user visualizes the geometry. To do so, it is necessary to install FreeCAD 0.16[1]. The *FCStd file (FreeCAD format) where the solar cell geometry is defined can be downloaded from the following link: test_Si_cell.FCStd.

When the geometry is visualized in FreeCAD, the object labels contain words in parentheses (see Fig. 3). These are the objects that will interact with the rays during the optical simulation; the text in the parentheses is the name of the optical material of the object.

Furthermore, the following files, which can be downloaded at https://github.com/bielcardona/OTSun (tests folder), are necessary for the simulation:

- File for the complex refractive index of the glass: BK7_Schott.txt
- File for the complex refractive index of the encapsulant: EVA.txt
- File for the complex refractive index of the PV material: Silicon.txt
- File for the complex refractive index of the substrate: Al.txt
- File for the complex refractive index of the AR 1 material: MgF2.txt
- File for the complex refractive index of the AR 2 material: Si3N4.txt

Once the user is acquainted with the geometry and has downloaded the aforementioned files, he or she can proceed with the configuration of the simulation using the OTSun WebApp, which is located at the following link: http://otsun.uib.es/otsunwebapp (Fig. 4).

[1] At this point, OTSun is not compatible with FreeCAD version 0.17, which was released only recently.

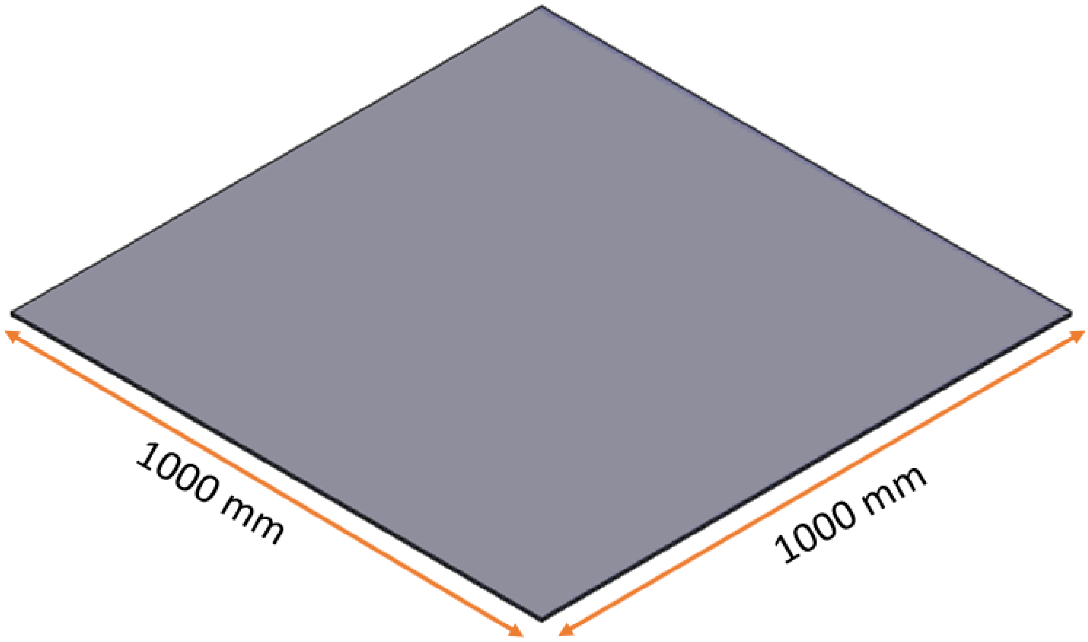

Fig. 1. Geometry and dimensions of the photovoltaic cell to be simulated.

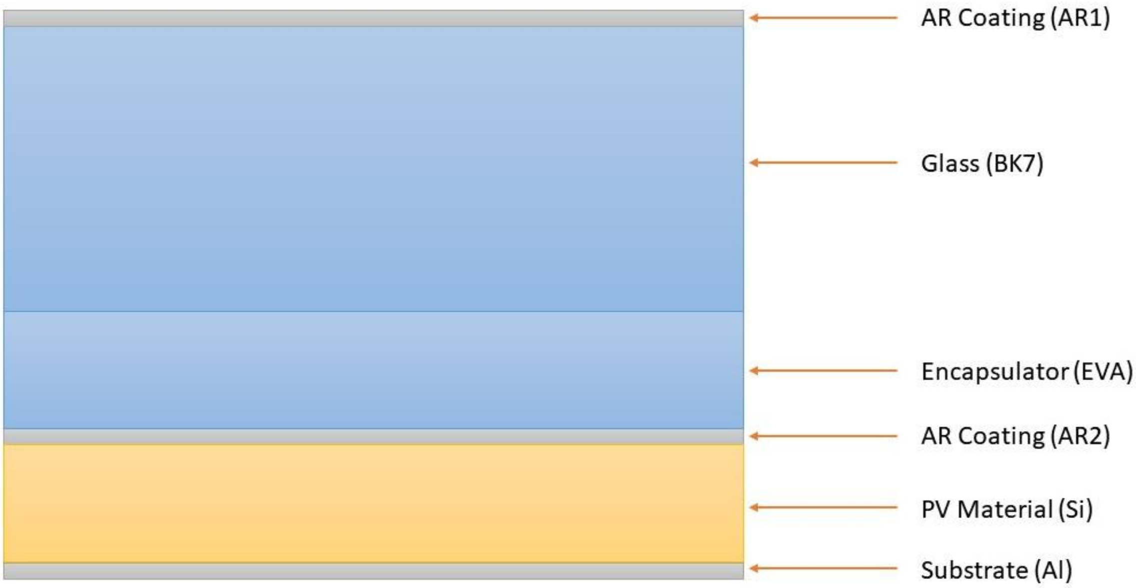

Fig. 2. Cross-sectional view showing the structure of the PV cell. In parentheses, the name of the material is shown. Not to scale.

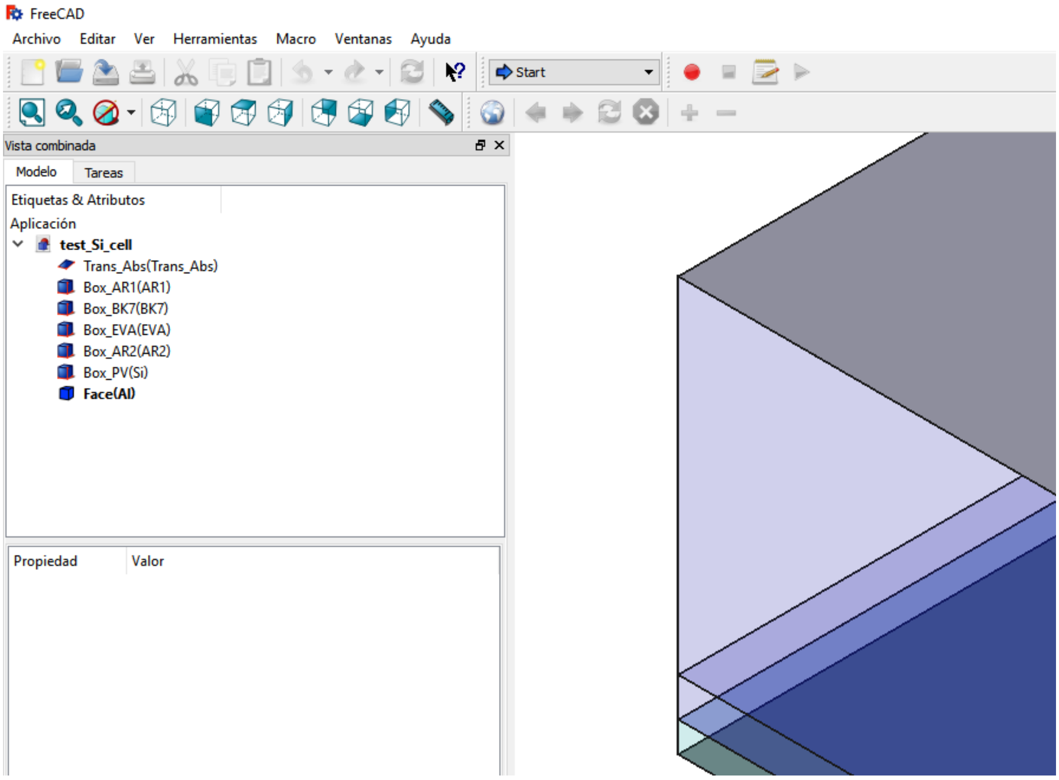

Fig. 3. Visualization of the solar cell in FreeCAD. The different collector components are listed in the panel on the left. Each object is shown together with its respective labels. The name of the material in parentheses must be included.

2. Getting started

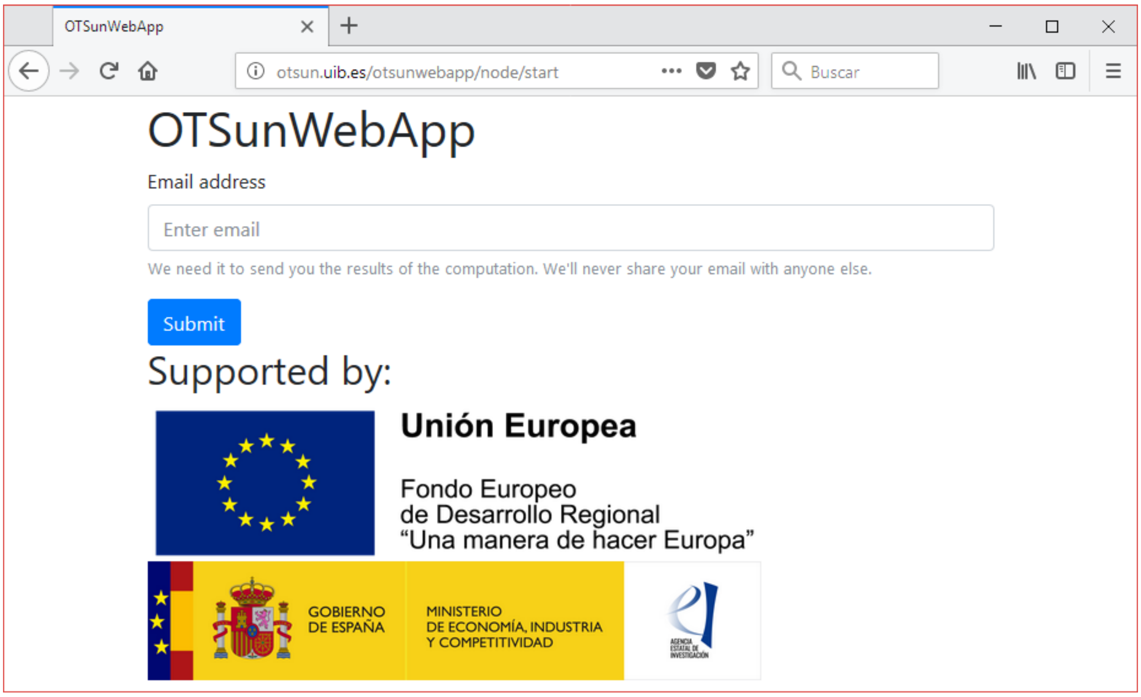

Fig. 1. Homepage of the OTSun WebApp.

1. Type in the email address where the user wants to receive the results of the simulation.
2. Click on “submit”.

3. Upload the geometry

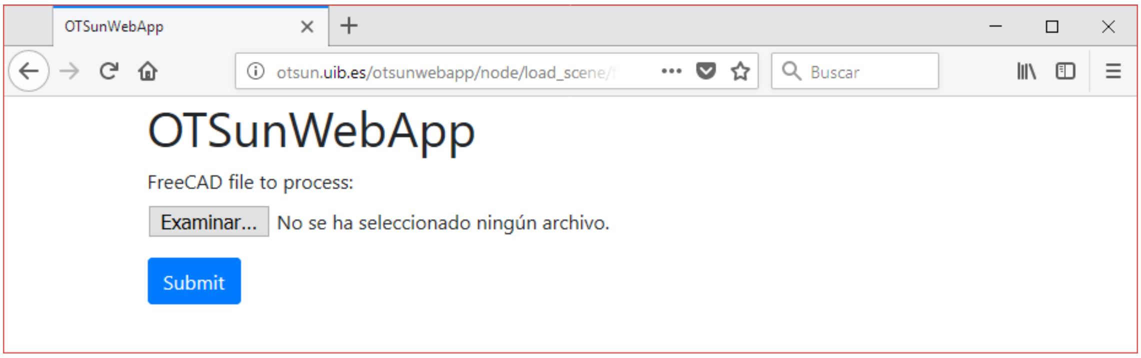

Fig. 2. Website to which the FreeCAD file (where the solar collector geometry is defined) should be uploaded.

1. Select the file test_Si_cell.FCStd, which contains the geometry of the solar thermal collector.
2. Click on “submit”.

4. Objects and materials

On the next webpage, the objects of the geometry of the uploaded solar collector appear (see Fig. 36). These objects are:

- Volume material: AR1, AR2, BK7, Si, EVA
- Surface material: Trans_Abs, Al

At this point, the optical properties of the objects of the geometry that interact with rays must be defined. For each object, a *.otmaterial file is needed. How to create such files is explained below.

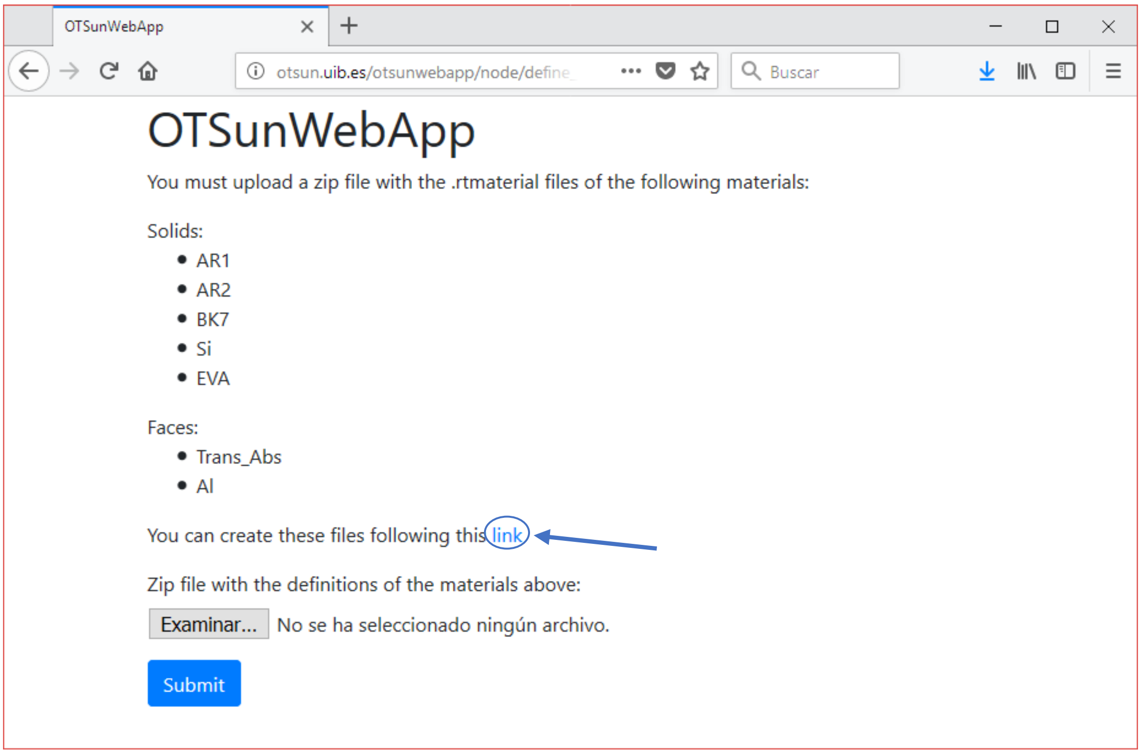

Fig. 3. Webpage which lists the different objects of the PV cell.

It is important to note that the names of the material files must be identical to the text in parentheses in the label of each respective FreeCAD object. Fig. 3 shows the label of each component in this particular case.

If the user has already created a *.zip file containing all the optical property material files:

1. Select the *.zip file that contains all the material files.
2. Click on "submit".

Otherwise, the user must create the files for each material manually:

1. Click on the hyperlink shown in Fig.6, which will redirect the user to the "*Creator of Materials*" site (http://otsun.uib.es/otsunwebapp/material). This link leads to the tab shown in Fig. 7.
2. Identify each of the materials with the names that appear in Fig. 6 (AR1, AR2, etc.). The following instructions describe how to create the material file called BK7, which is the label for the glass of the PV cell.
3. Select "Volume" from the "Kind of material" drop-down list, since it is a volume material (Fig. 3).
4. Select "Variable refractive index" from the "Kind of volume material" drop-down list (Fig. 8), since it is a volume material with a variable refractive index as a function of wavelength.
5. Upload the text file which contains the refractive indices of the glass: BK7_Schott.txt.
6. Click on "submit". At this moment, the application has generated a file for this material called "BK7.otmaterial".

7. For the rest of the materials, the same steps must be followed, choosing the characteristics described in Table 1 for each one of them.
8. Once all the material files have been created, they should be stored in the same local folder and compressed into a single *.zip file, as illustrated in Fig. 8.
9. Go back to the previous tab and upload the *.zip file.
10. Click on “submit”.

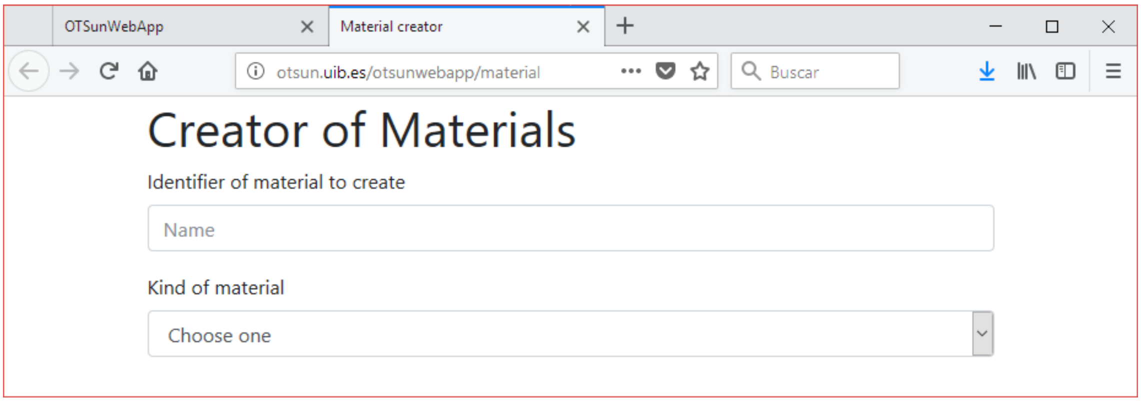

Fig. 4. Webpage for the manual generation of material files.

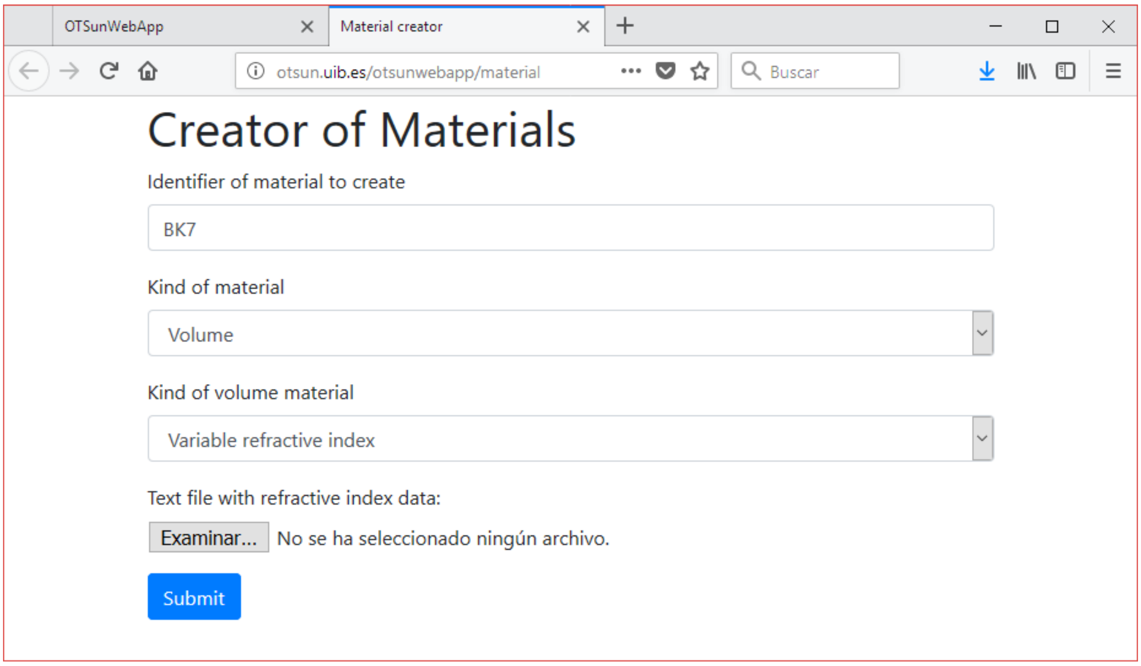

Fig. 5. Webpage for the creation of OTSun material files.

With regard to the Trans_Abs material, this is a virtual material on top of the photovoltaic cell, which the algorithm uses internally to calculate the total reflection of the device. It has been created as a hybrid of two standard material templates: Trans and Abs.

Trans represents a completely transparent surface material (“*Transparent simple layer*”), with a probability of transmission equal to one, whereas Abs represents a completely absorptive surface material (“*Absorber simple layer*”), with a probability of absorption equal to one.

Both materials can be created using the web app, as demonstrated in Fig. 6. Trans_Abs is defined as a surface material ("*Create material from two layers*") with the Trans layer on top and the Abs layer at the bottom. The Trans_Abs surface allows all the radiation from above to pass, but simultaneously absorbs all radiation from below (see Fig. 7).

In this way, the total reflection of the solar cell is directly obtained. Please note that the Abs material absorbs all of the incident radiation, and consequently this absorber material for the PV cell must be defined in the same way as has been done for the solar thermal collectors (see Table 1), which means that its aperture area must be provided (Section 5).

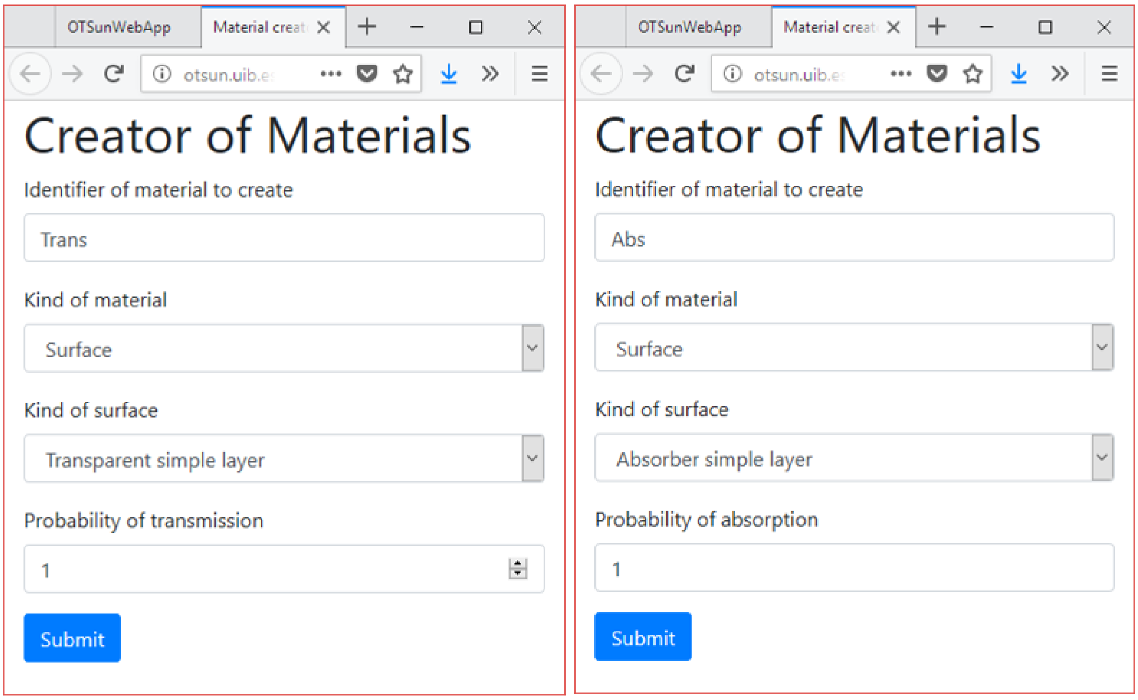

Fig. 6. Screenshot of the optical properties of the "Trans" and "Abs" materials that are necessary to generate the "Trans_Abs" virtual material.

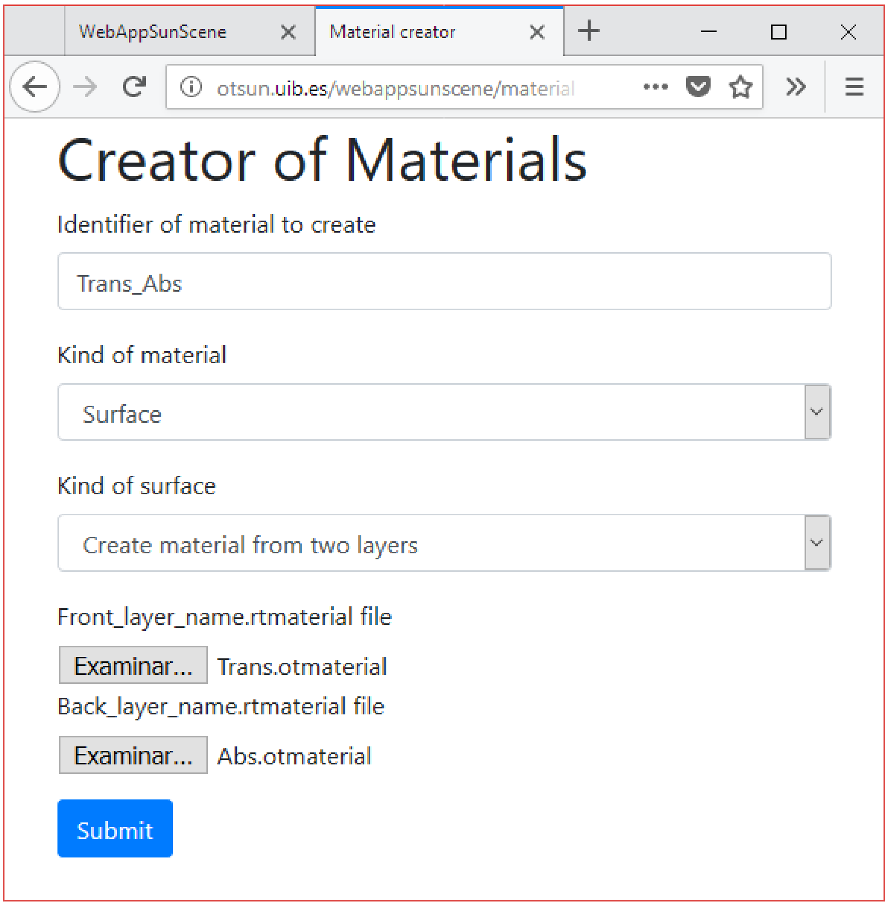

Fig. 7. Screenshot showing the optical properties of the "Trans_Abs" virtual material.

Table 1. Characteristics of the materials.

Material	**Name**	**Type**	**Optical properties**
Trans Abs	Trans_Abs	*Surface – Create Material from Two Layers*	Trans.otmaterial Abs.otmaterial
Anti-reflective Coating 1	AR1	*Volume – Variable Refractive Index*	MgF2.txt: MgF_2 [1]
Glass	BK7	*Volume – Variable Refractive Index*	BK7_Schott.txt
Encapsulant	EVA	*Volume – Variable Refractive Index*	EVA.txt
Anti-reflective Coating 2	AR2	*Volume – Variable Refractive Index*	Si3N4.txt
PV material	Si	*Volume – PV Material*	Silicon.txt
Conductor	Al	*Surface – Reflector Specular Metallic Layer*	Al.txt

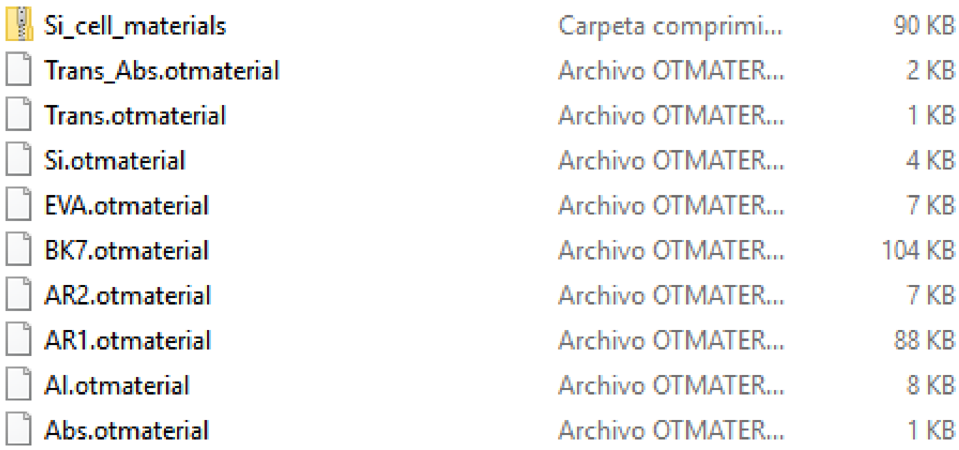

*Fig. 8. Directory containing the OTSun material files of each component, and the collective *.zip folder.*

5. Inputs for the simulation (experiment)

In the drop-down list shown in Fig. 12, there are three types of analysis to perform in the simulation. In this case, the user will select "*Spectral analysis (single direction)*", the purpose of which is to obtain the optical efficiency in the function of the wavelength in a single source position. The results are presented in *.txt files.

In this example, the simulation is at normal incidence. The number of rays for each wavelength is 1000 and the wavelength range is 250 to 1300 nm, with a step of 5 nm. This number of rays has been chosen so that the calculation is quick. To obtain a more reliable result, the use of at least 10000 rays per wavelength is recommended. The aperture area of the solar cell is 1000000 mm^2. Note that as this is a solar photovoltaic panel, this is the aperture area for both thermal and PV. Finally, the sun is considered as a point source, hence the Circum Solar Ratio (CSR) value is not specified (default value is zero).

The parameters are summarized below:

1. Select "Spectral analysis (single direction)" and click on "submit". The simulation parameters will then be defined (see Fig. 13).
2. Sun position*:* $\phi = 0^o$, an d $\theta = 0^o$.
3. Wavelength: $\lambda_i = 250$ nm, $\lambda_f = 1300$ nm. Step = 5 nm.
4. Number of rays: 1000.
5. Collector aperture area for PV: 1000000 mm^2. This is the aperture area of the solar cell.
6. Collector aperture area for thermal: 1000000 mm^2. This is the aperture area of the Trans_Abs material.
7. CSR value: 0.
8. Click on "submit".

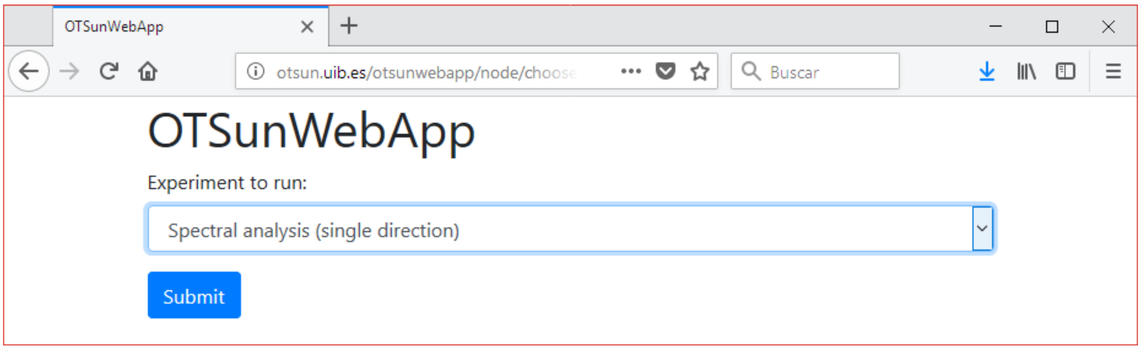

Fig. 9. Drop-down list from which the type of simulation is chosen. In this case "Spectral analysis (single direction)" will be conducted.

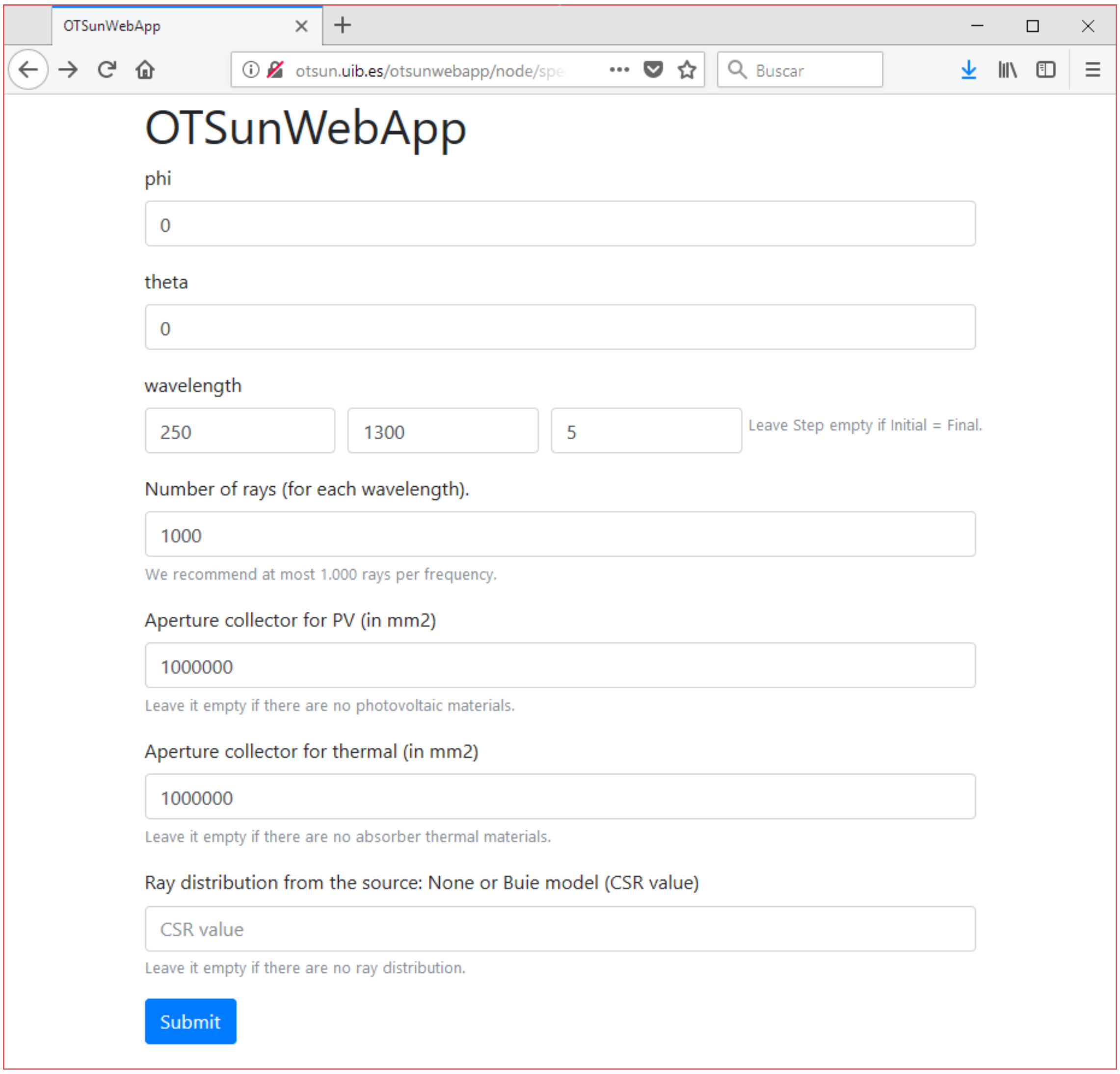

Fig. 10. Form to fill in the ray-tracing configurations.

6. Run simulation

At this point, the application displays the webpage illustrated in Fig. 11. The instructions presented on this webpage must be followed to start the simulation process. By clicking on “OK”, the user will reach the webpage illustrated in Fig. 12, which will show an error message if the simulation could not be executed. If there are no errors, a link appears from which the simulation status can be accessed (see Fig. 16). On this webpage, if the user refreshes the webpage, the simulation progress is displayed.

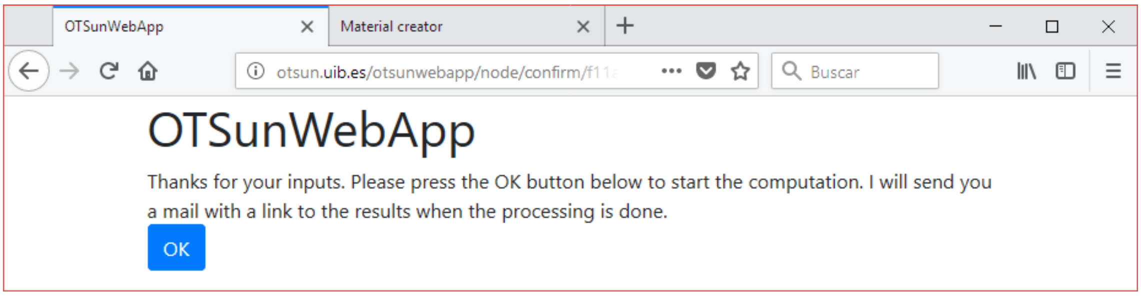

Fig. 11. Confirmation message after all ray-tracing settings have been uploaded successfully.

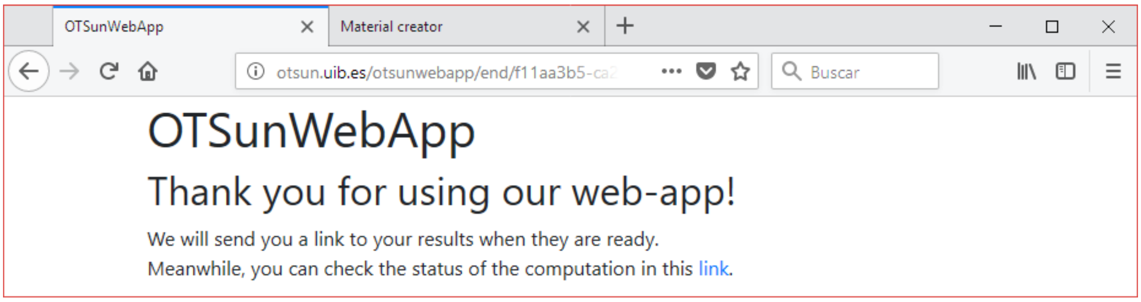

Fig. 12. “Thank you” message. The link that appears leads the user to the webpage with the computation status.

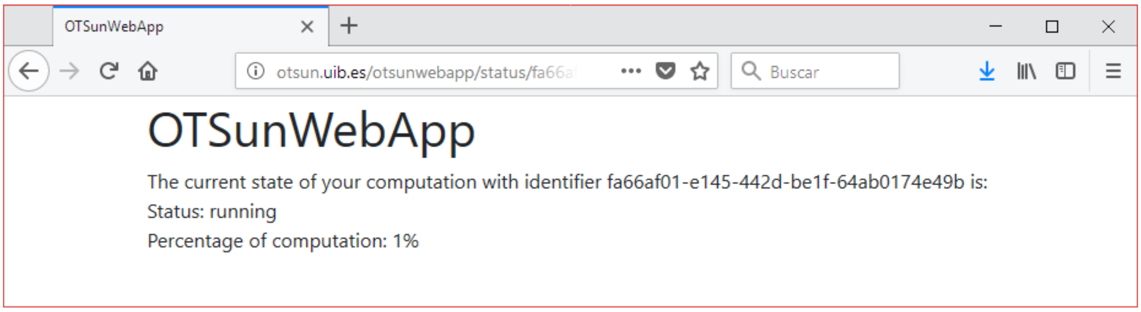

Fig. 13. Webpage with the computation status.

7. Results

Once the simulation has finished, the user will receive an email that includes the message "Get your results at: *link*". By clicking on this link, an "output.zip" file that contains the results of the simulation will be automatically downloaded. The results are stored in six different files, as shown in Fig. 14.

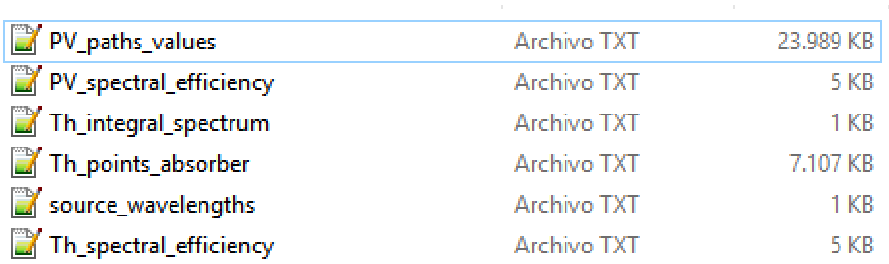

*Fig. 14. Files that contain the results of the simulations. All files are located in the *.zip file that the user receives via email.*

7.1 PV_paths_values.txt

The "*PV_paths_values.txt*" file contains information about the paths of different rays as they were traced while interacting with the photovoltaic material. The information is stored in the following order:

- Coordinates of the point at which the ray first intersects/enters the PV material.
- Coordinates of the point at which the ray leaves the PV material.
- Energy of the ray when entering the PV material.
- Energy of the ray when leaving the PV material.
- Wavelength of the ray (nm).
- Absorption coefficient of the PV material at the given wavelength (mm^{-1}).
- The incidence angle of the ray (degrees).

Fig. 15 presents the different variables of the file schematically. Where α is the absorption coefficient of the material, λ is the wavelength of the incident radiation, ε is the energy of the ray and (x, y, z) are the coordinates of the intersection points.

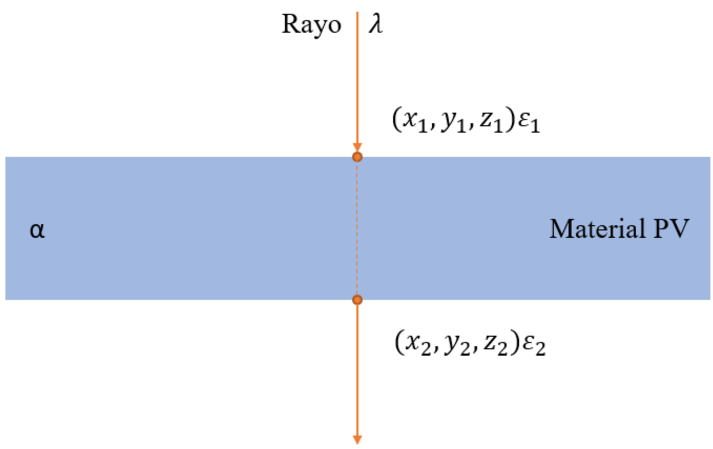

Fig. 15. Graphical representation of the variables contained in "PV_paths_values.txt".

7.2 PV_spectral_efficiency.txt

The "*PV_spectral_efficiency.txt*" file contains the optical efficiency of the photovoltaic cell as a function of wavelength of the incident light. This efficiency is illustrated in Fig. 16, which represents the content of the file graphically.

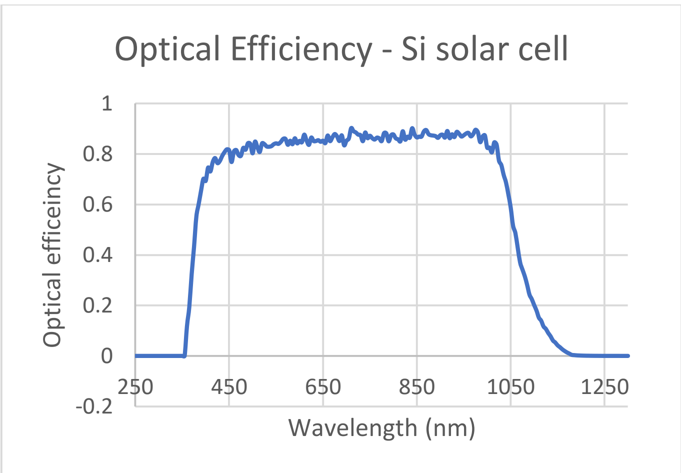

Fig. 16. Optical efficiency of the PV cell as a function of the wavelength.

7.3 Th_integral_spectrum.txt

"*Th_integral_spectrum.txt*" contains information on the power energy absorbed by the Trans_Abs material, the overall emitted radiation at the source (according to the Reference Air Mass 1.5 Spectra for direct solar radiation ASTMG173), and the efficiency of the absorber material.

Th_integral_spectrum.txt

```
#power_absorbed_from_source_Th irradiance_emitted(W/m2) efficiency_from_source_Th
173.76438117547096 781.6331257477002 0.2223093871683729
```

Fig. 17. Screenshot of the parameters contained in the "Th_integral_spectrum.txt" file.

7.4 Th_points_absorber.txt

"*Th_points_absorber.txt*" contains information on the rays at their points of intersection on the absorber material. The information is stored in four columns:

- Energy of the incident ray on the absorber material[2].
- Coordinates of the point of intersection on the absorber material.
- Coordinates of the previous point of intersection on the absorber material.
- Normal vector of the absorber surface.

Th_points_absorber.txt

```
#energy_ray point_on_absorber[3] previous_point[3] normal_at_absorber_face[3]
1.000000 -295.786917 -407.616711 0.000050 -295.786917 -407.616711 -0.000000 0.000000 0.000000 1.000000
1.000000 353.402570 -16.720784 0.000050 353.402570 -16.720784 -0.000000 0.000000 0.000000 1.000000
0.926221 -22.925744 -463.845017 0.000050 -22.925744 -463.845017 -0.000000 0.000000 0.000000 1.000000
0.926221 -491.503422 -200.167990 0.000050 -491.503422 -200.167990 -0.000000 0.000000 0.000000 1.000000
1.000000 -314.141255 350.930515 0.000050 -314.141255 350.930515 -0.000000 0.000000 0.000000 1.000000
0.926221 -326.737691 -57.380991 0.000050 -326.737691 -57.380991 -0.000000 0.000000 0.000000 1.000000
```

Fig. 18. Screenshot of the values contained in the "Th_points_absorber.txt" file.

7.5 source_wavelengths.txt

The "*source_wavelengths.txt*" file contains information about the source of radiation. The parameters of this file can be found in Fig. 189.

source_wavelengths.txt

```
1.0 # Collector Th aperture in m2
1.0 # Collector PV aperture in m2
250.0 # Wavelength initial in nm
1300.0001 # Wavelength final in nm
5.0 # Step of wavelength in nm
1000 # Rays per wavelength

```

Fig. 189. Screenshot of the parameters contained in the "source_wavelength.txt" file.

[2] Note that when each ray is emitted from the source has an energy equal to one. Then when the ray travel through the scene this energy could be attenuated till a value of 10^{-6}.

7.6 Th_spectral_efficiency.txt

"*Th_spectral_efficiency.txt*" contains information on the optical efficiency of the absorber material as a function of wavelength. As previously mentioned, the optical efficiency corresponds to the total reflectance of the PV cell depending on the wavelength. 20 illustrates the relationship between reflectance and wavelength.

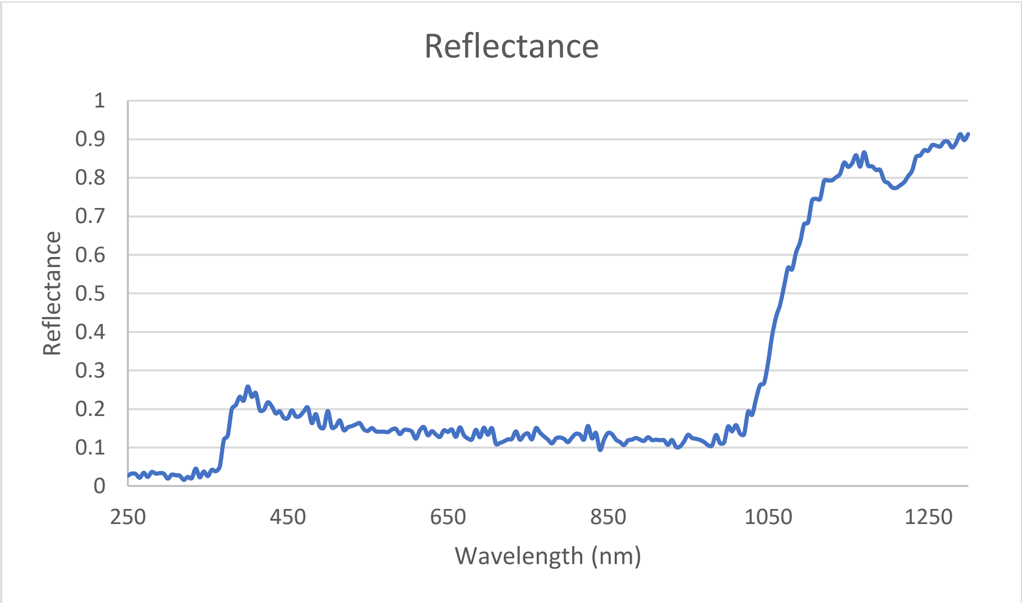

Fig. 20. Total reflectance of the PV cell as a function of the wavelength of the incident radiation.

References

1. J. D. Hertel, F. Bonnín-Ripoll, V. Martínez-Moll, and R. Pujol-Nadal, "Incidence-Angle- and Wavelength-Resolved Ray-Tracing Simulations of a Linear Fresnel Collector Using the In-House Software otsun," J. Sol. Energy Eng. **140**(3), 034502 (2018).