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Metamaterials for Concentrated Solar Power applications

IBON REMENTERIA - A20359681

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Energy generation

- Human beings consume energy on their everyday life
- Traditionally, it has been produced using non-renewable resources such as fossil fuels or nuclear energy

Source: www.kidzworld.com

Energy generation

- This tendency is changing due to the development of renewable energies such as:
  - Wind Power

Credits for the picture: By 林 慕尧 / Chris Lim from East Coast (东海岸), Singapore (新加坡) - Windmills in China?{D70 series}, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=2909338

Energy generation

- This tendency is changing due to the development of renewable energies such as:
  - Hydropower

Source: www.emaze.com

Energy generation

- This tendency is changing due to the development of renewable energies such as:
  - Solar Power

Source: www.inhabitat.com

Solar Energy

- However, there are many technologies inside the solar power:
  - Solar Thermal: Water is heated to be used as Domestic Hot Water (DHW), it's goal is to heat rooms through the heating, or be used as shower water – no electricity is generated.

Source: www.mvmsolar.com

Solar Energy

- However, there are many technologies inside the solar power:
  - Photovoltaics: DC electricity is generated from the use of semiconductors in these panels.

Source: www.iene.eu

Solar Energy

- However, there are many technologies inside the solar power:
  - Concentrated Solar Power (CSP): Sun light is concentrated in a single point (or row) so that thermal energy is efficiently converted to electricity

Source: www.pfenninger.com

Types of CSP: Med./Low temperatures (T<400ºC)

- Linear concentrator systems: parabolic

Source: Solar Energy Industries Association

Types of CSP: Med./Low temperatures (T<400ºC)

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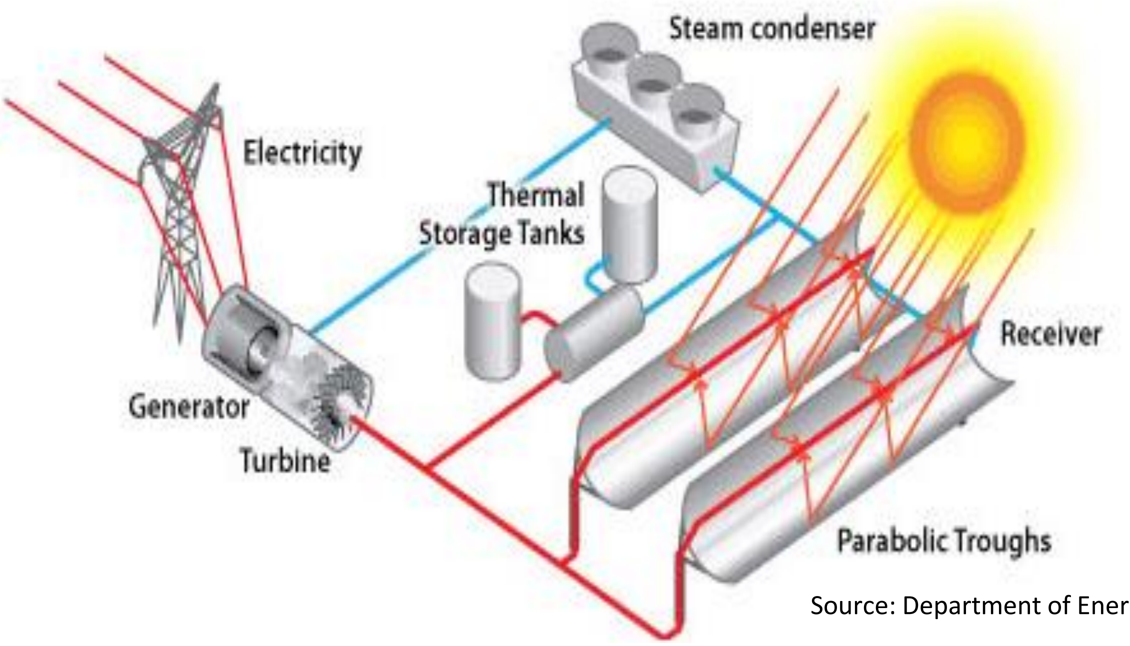
- Linear concentrator systems: parabolic
  - Light is concentrated in a long pipe using a parabolic trough, where a liquid is heated and vaporized in order to the steam to move a turbine to produce electricity



Source: Department of Energy

Types of CSP: Med./Low temperatures (T<400ºC)

- Linear concentrator systems: linear Fresnel

Source: AREVA Solar

Types of CSP: Med./Low temperatures (T<400ºC)

- Linear concentrator systems: linear Fresnel
  - Light is concentrated in a long pipe by using a number of long and thin movable flat mirrors, where a liquid is vaporized and moved towards a turbine to produce electricity.

Source: Open Source Ecology

Types of CSP: Med./Low temperatures (T<400ºC)

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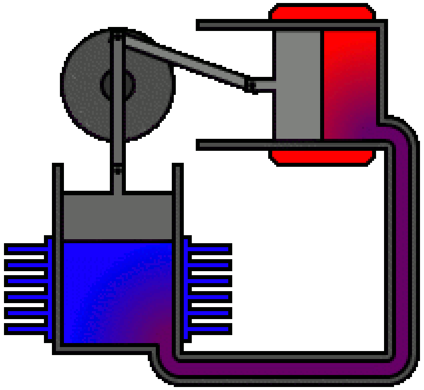
- Dish/Engine systems: Stirling

Source: Wikimedia

Types of CSP: Med./Low temperatures (T<400ºC)

- Dish/Engine systems: Stirling
  - Light is concentrated in a single point and air or another gas is heated. As it expands it moves a piston, the fluid is displaced and cooled down so the piston goes back to the initial position, generating the rotatory movement needed to generate electricity.

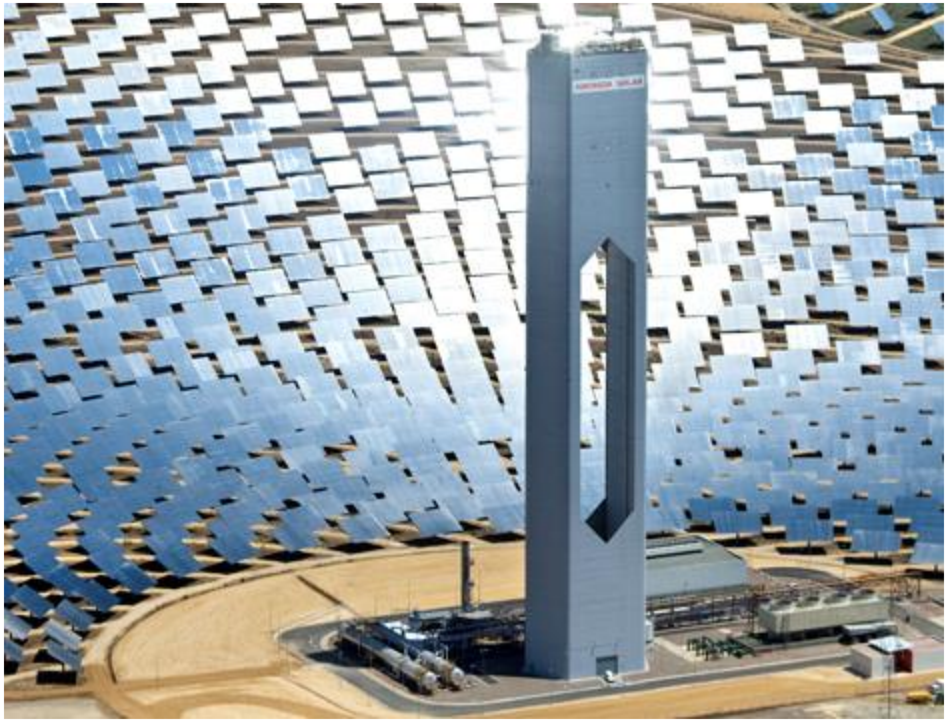
Source: Gigaohm



Credits: By Zephyris at the English language Wikipedia, CC BY-SA 3.0

Types of CSP: High temperatures (T>400ºC)

- Solar Power Tower (SPT)



Source: Abengoa Solar

Types of CSP: High temperatures (T>400ºC)

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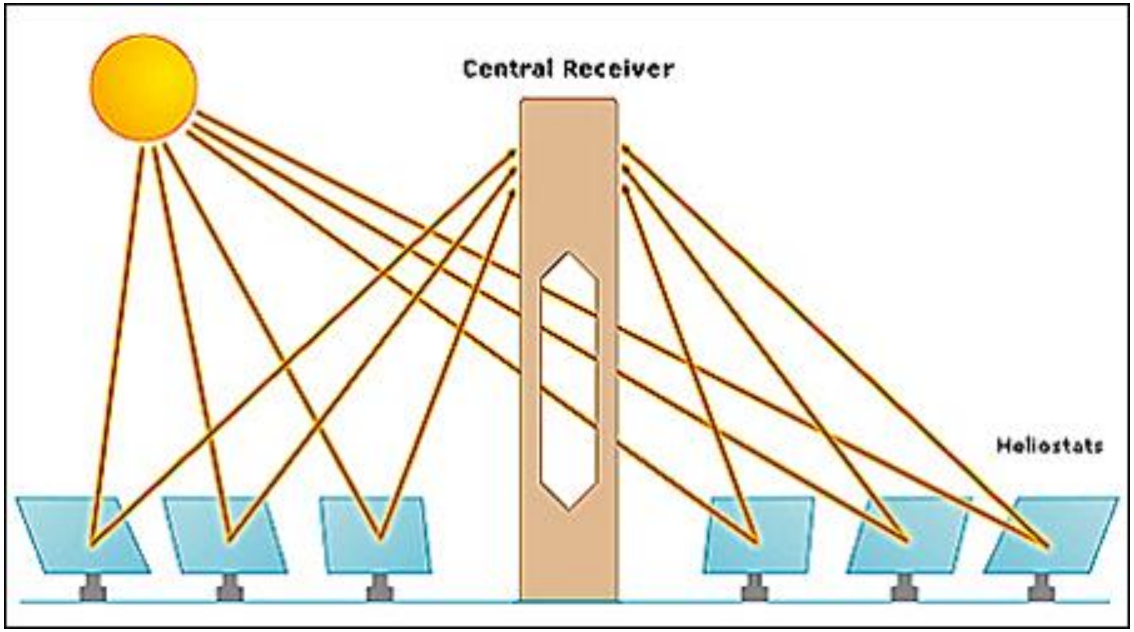
- Solar Power Tower (SPT)
  - A number of mirrors (called heliostats) concentrate the light on top of a tall tower where water or salts are heated to create vapor water. This is later directed to the generator, where electricity is generated.



Source: SolarCellCentral.com

Solar Power Tower

- The Solar Power Tower type of Concentrated Solar Power is still in its first development stages; the first ever created commercially oriented SPT was built in 2006 by Abengoa Solar in Spain.
- Several plants have been constructed since then, each one adding new improvements from what has been learnt from previous constructions.
- As a consequence, new SPT plants have been improving their production capacity, as can be seen in the yearly production of each of the currently active SPT’s, on the following slide.

Solar Power Tower

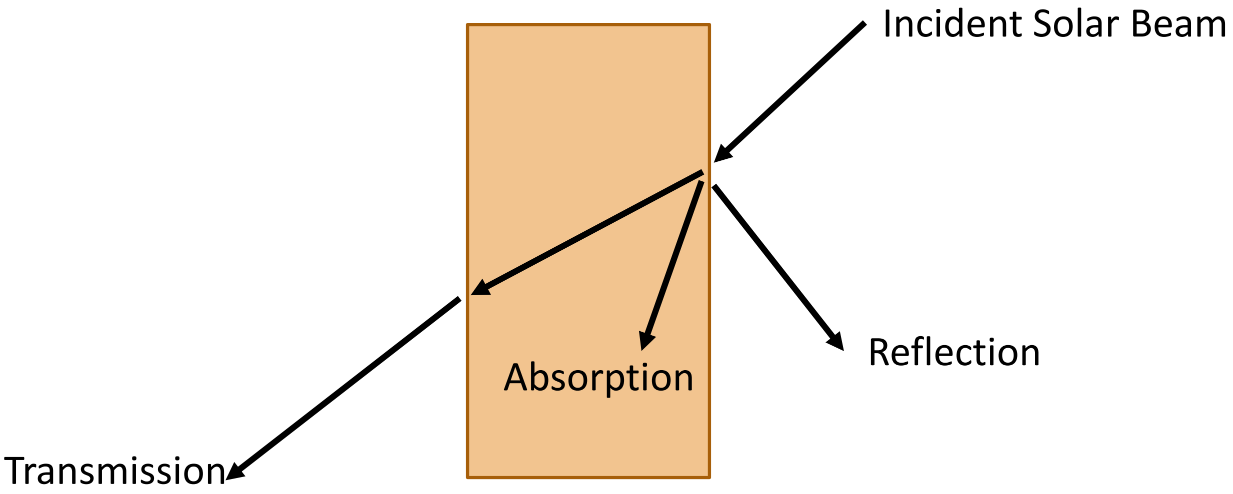
- To further understand what is actually happening on top of the SPTs, some basic notions of radiation are explained below.

- This notions will help understand where and how improvements can be done in currently active SPTs.

Basics of radiation

- When an incident light beam impacts a surface, three possible things can happen: the beam can be reflected, absorbed or transmitted
- Following Kirchoff's law, the sum of the three components must be the same as the incident beam:

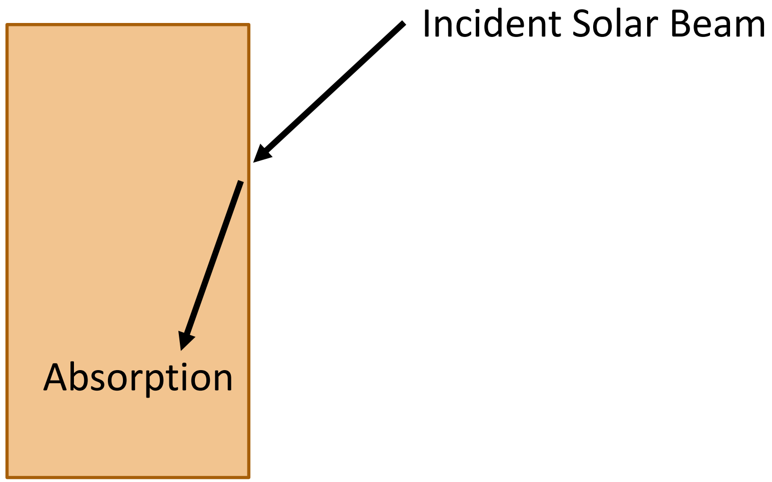
Incident Solar Beam = Absorption + Reflection + Transmission



Basics of radiation

Absorption:

- Electrons on surfaces are vibrating at their natural frequency. If they are hit with a wavelength that vibrates in the same frequency, electrons absorb it and through movement transform it in thermal energy.



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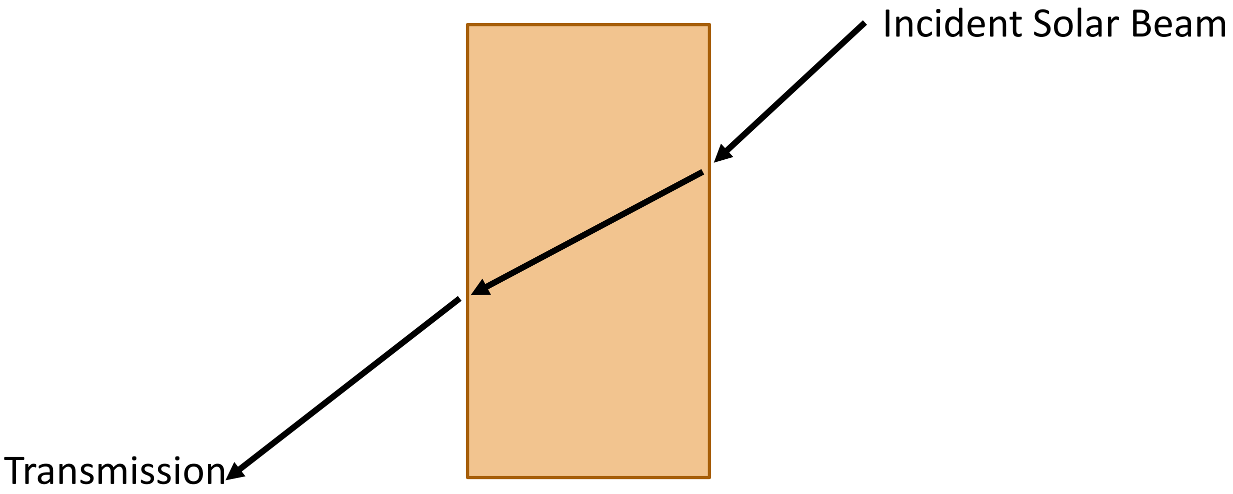
Basics of radiation

Transmission:

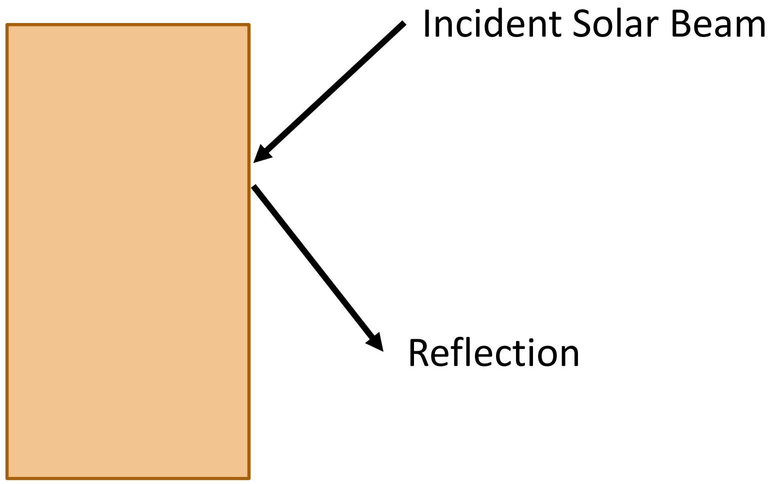
- When hitting wavelength does not match the natural frequency of the electrons, they vibrate for short periods of time. Then the energy is emitted as a wavelength. If the object is transparent, the process continues through the width of it, until it exits the object.



Basics of radiation

Reflection:

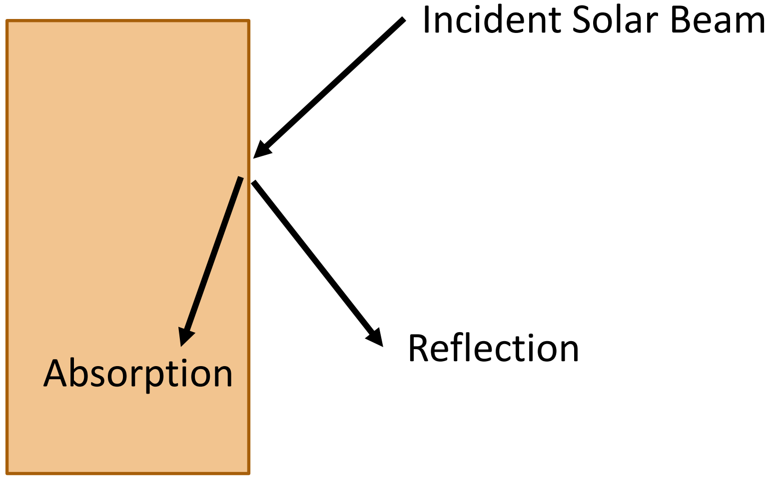
- When hitting wavelength does not match the natural frequency of the electrons and the object is opaque, the energy emitted as a wavelength is not absorbed by the atoms through the material.



Basics of radiation

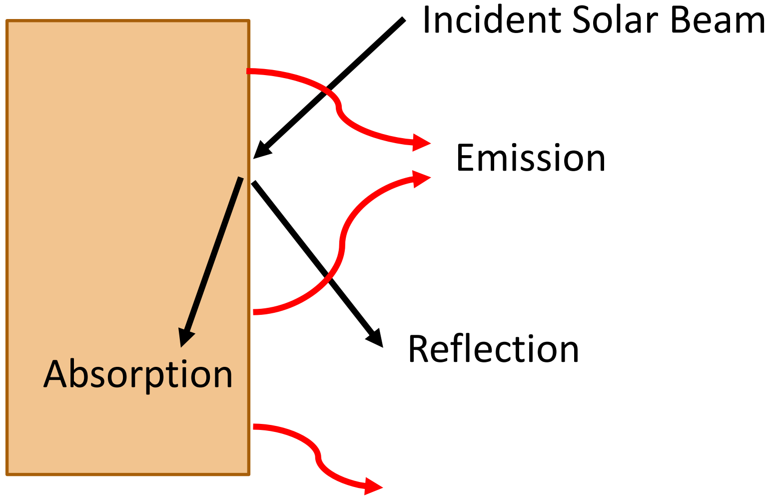
- In opaque objects, the total transmitted energy is zero, so Kirchoff’s equation is as follows:

Absorption(%) + Reflection(%) = Incident Solar Beam(100%)



Basics of radiation

- In opaque objects, if the object has an absorption, its energy increases, thus its temperature raises
- Assuming the object is in steady state and therefore at constant temperature, it must emit everything that absorbs.

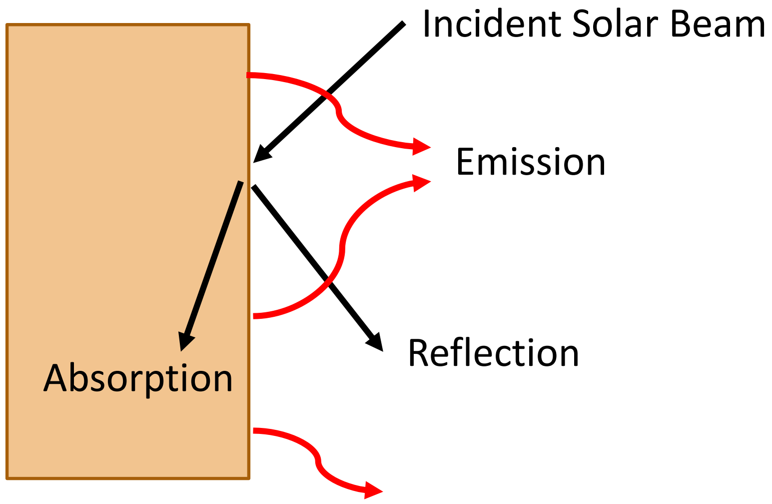


Basics of radiation

- Therefore, Emission = Absorption, turning Kirchoff’s equation into

Emission(%) + Reflection (%) = Incident Solar Beam (100%)

- Thus, **less** reflection = **more** emission

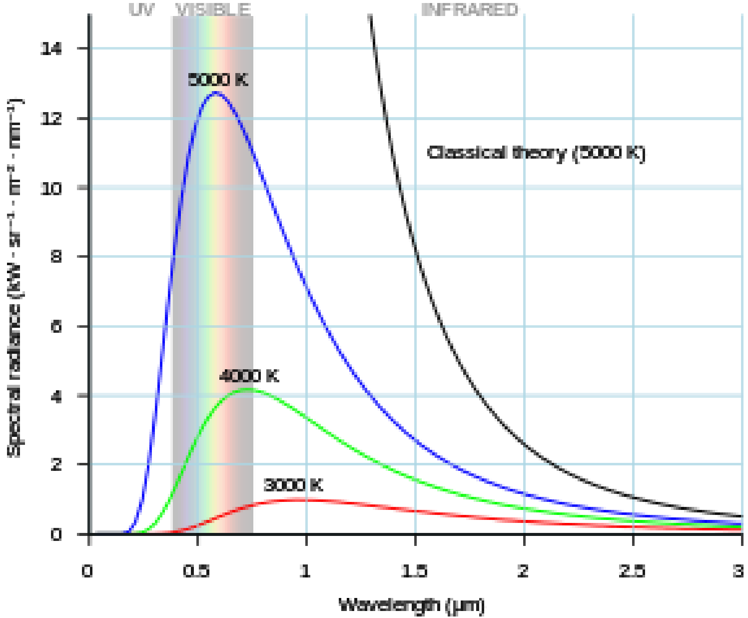


Basics of radiation

Blackbody:

- A blackbody is defined as a body can emit (and absorb!) the maximum theoretically possible amount of radiation, defined by Stefan Boltzmann's equation:

$E=\sigma T^4$ $\sigma = 5.67 \times 10^{-8}\ {}^{W}/_{m^2K^4}$



Source: Wkimedia.com

Basics of radiation

Emissivity:

- It is defined as the effectiveness of a material in emitting energy as thermal radiation. It is a factor that varies from 0 to 1, depending on how similar to a blackbody an object is.
- When placed inside the Stefan Boltzmann's equation, it shows the total radiation emitted by a body

$$E = \textcircled{\varepsilon}\,\sigma\, T^4$$

- Examples:
  - Emissivity=1 → Same as Blackbody
  - Emissivity=0.4 → Emits 40% of a blackbody at that temperature
  - Emissivity=0 → Not emission at all

Basics of radiation

Greybody:

- It is defined as a body that has a constant value of emissivity through all wavelengths
- In case it varies due to roughness (reflection may be affected), it varies in the same way in all wavelengths

Basics of radiation

Non-greybody:

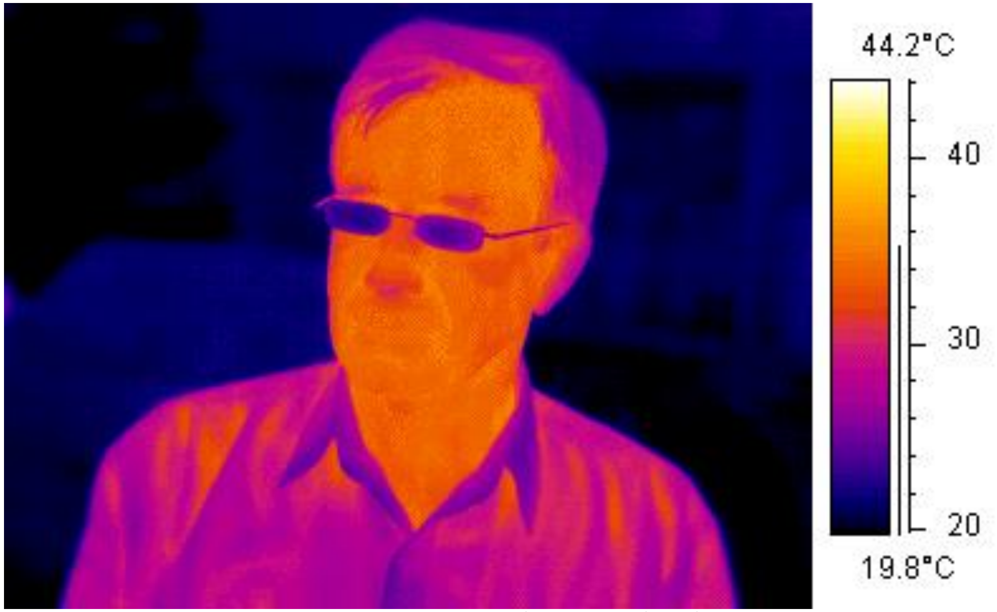
- This types of bodies are the ones that have a variable value of emissivity for different wavelengths
- Plastic bags for example are opaque to visible wavelengths, but transparent to infrared wavelengths

Source: physics.stackexchange.com

Basics of radiation

Thermal radiation:

- When a body is heated up, the particles inside it start moving. This thermal motion of charged particles generates an electromagnetic radiation that is emitted and can be measured.



Source: physics.stackexchange.com

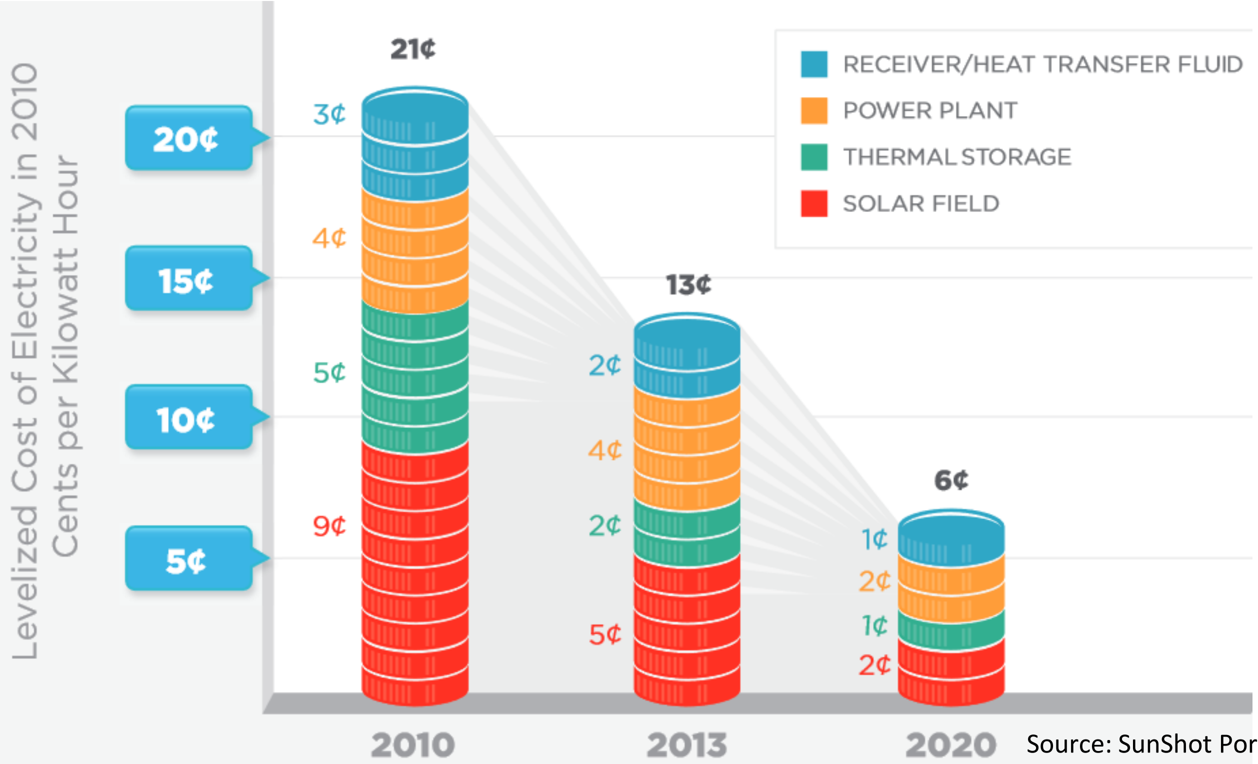
Current coatings

- Nowadays, the most common coating being used on the receivers of the SPTs is the Pyromark® 2500 series paint, that have a solar absorptivity (α) of 0.96 and an emissivity (ε) of 0.86

- The absorptivity value is a really good one, but the emissivity still can be much lower to avoid large IR emissions.

Current objectives

- The objective of the CSP industry is to lower the cost of the KWh of this type of technology to 6 cents by 2020



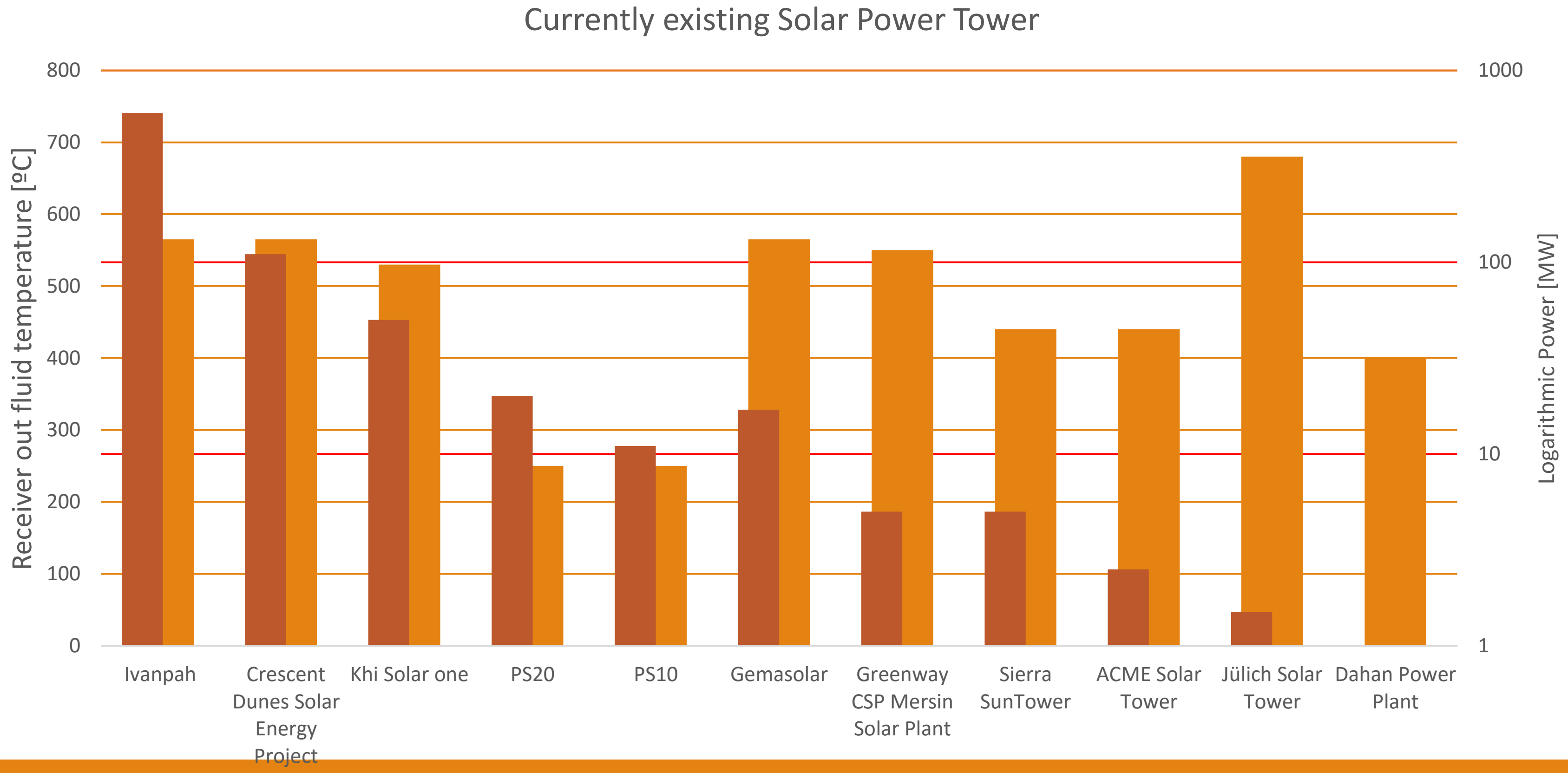
Source: SunShot Portfolio

Currently active Solar Power Tower plants

Power plants	Installed capacity (MW)	Yearly production (GWh)	Country	Developer/ Owner	Completed
Ivanpah Solar Power Facility	600	420	USA	BrightSource Energy	2013
Crescent Dunes Solar Energy Project	110	500	USA	SolarReserve	2013
Khi Solar One	50	-	South Africa	Abengoa	2016
PS20 solar power tower	20	44	Spain	Abengoa	2009
Gemasolar	17	100	Spain	Sener	2011
PS10 solar power tower	11	24	Spain	Abengoa	2006
Jülich Solar Tower	1.5		Germany		2008
Greenway CSP Mersin Solar Plant	5		Turkey	Greenway CSP	2013
Sierra SunTower	5		USA	eSolar	2009
ACME Solar Tower	2.5		India	ACME Group	2011
Dahan Power Plant	1		China	Inst. of Elec. Eng. of Chinese Academy of Sciences	2012

Current objectives

- To do so, the current objective for the hot fluid’s exit temperature to be higher than 650ºC.



Current objectives

- On the other hand, the current objective for the thermal efficieny of the receiver is to be higher than 90%
- To achieve that a lot of research is being done in improving several aspects of the production
- An analysis of different efficiencies and their effects is shown in the following slides

Efficiency

Four main efficiency values existing:

- Mirror efficiency: How efficiently light beams are reflected in the Heliostats
- Receiver efficiency: How efficiently solar irradiation is transformed into thermal energy
- Carnot efficiency: How efficiently thermal energy is turned into mechanical energy
- AC conversion efficiency: How efficiently mechanical energy is transformed into electrical energy

Efficiency

Relevance of the efficiencies to this project:

- Mirror efficiency: It is going to be ignored as it usually is around 90-97% and is not the objective of this research
- Receiver efficiency: Important and relevant to this research
- Carnot efficiency: Important and relevant to this research
- AC conversion efficiency: It is going to be ignored as it is not the objective of this research

Efficiency

Carnot efficiency:

- Measures the efficiency of thermal to mechanical transformation of energy
- The hotter the hot source and the colder the cold source the better efficiency
- Hot source’s temperature is the temperature at which water or salts are heated on top of the tower, and the cold temperature is the temperature of the water or salts entering the tower to be heated

$$\eta_{th} \leq 1 - \frac{T_C}{T_H}$$

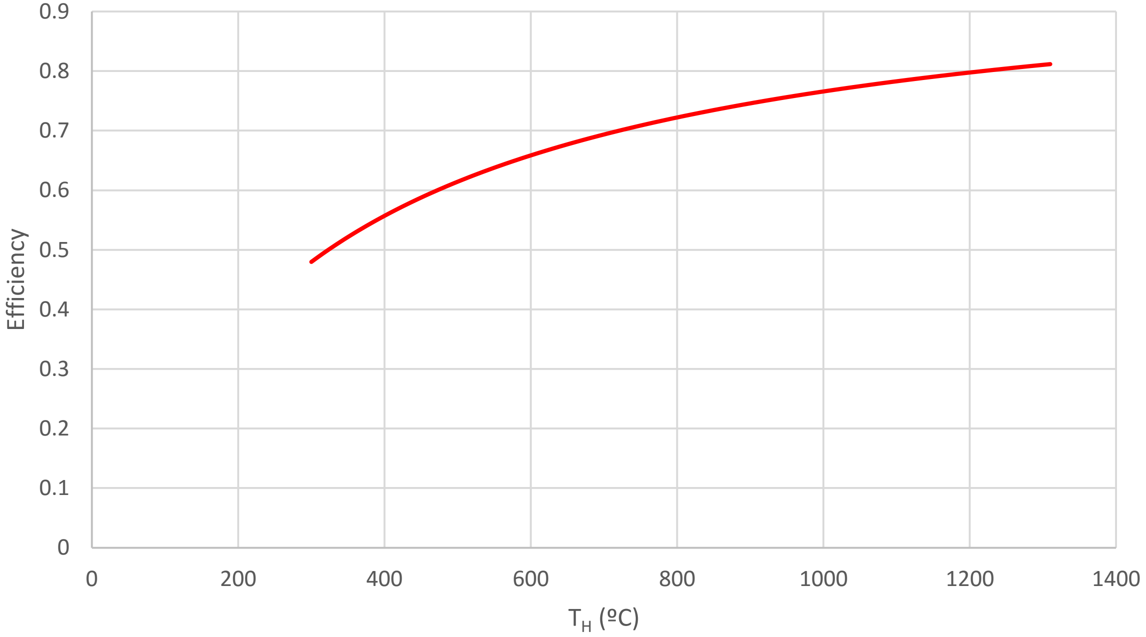
Efficiency

Carnot efficiency:

- Assuming T_C=25ºC

$$\eta_{th} \leq 1 - \frac{T_C}{T_H}$$

Efficiency vs T_H



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Efficiency

- It might seem logical then to put as many heliostats as possible to heat the fluid as much as possible
- However, as mentioned before, Carnot efficiency is not the only one playing an important role in the overall efficiency
- Receiver’s efficiency complicates the calculation of the optimum working temperature, as the hotter a body is the more infrared radiation it emits
- The more IR emission a body has the faster it cools down!

Efficiency

Receiver's efficiency:

- It is defined as a function between the total solar radiation impacting the receiver on top of the tower (Q_{solar}), the ammount of radiation actually absorbed by the receiver ($Q_{absorbed}$) and the ammout of radiation the receiver emmits due to IR radiation (Q_{lost})

- $Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$
- $Q_{absorbed} = \alpha \cdot Q_{solar}$
- $Q_{lost} = A \cdot \varepsilon \cdot \sigma \cdot T_H^4$

$$\eta = \frac{Q_{absorbed} - Q_{lost}}{Q_{solar}}$$

Efficiency

Receiver's efficiency: Q_{solar}

- Q_{solar} is the total ammount of radiation that impacts the receiver, and it is defined as follows:

$$Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$$

- Where η_{optics} is the Mirror's efficiency (≈1), C is the Concentration value, A stands for the Receiver's area (in m^2) and I is the Solar Irradiance (in W/m^2)

Efficiency

Receiver's efficiency: $Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$

- Concentration is a measure of how concentrated the sunlight is. The more Heliostats, the more concentrated the sunlight will be. It can be calculated as the ratio of the incoming radiation's area $A_{Heliostats}$ to the outgoing radiation's area $A_{receiver}$*

$$C = \frac{A_{Heliostats}}{A_{Receiver}}$$

- Where $A_{Heliostats}$ is the total area of the installed heliostats and $A_{Receiver}$ is the area of the receiver on top of the tower

*Robert Pitz-Paal, High Temperature Solar Concentrators, Solar Energy Conversion And Photoenergy Systems, Vol I

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Efficiency

Receiver's efficiency: $Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$

- Using Plack's law to calculate the Spectral Irradiance (I),

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

- Where h is the Plack constant, K_B the Boltzmann constant, c the speed of light, λ is the wavelength and T temperature

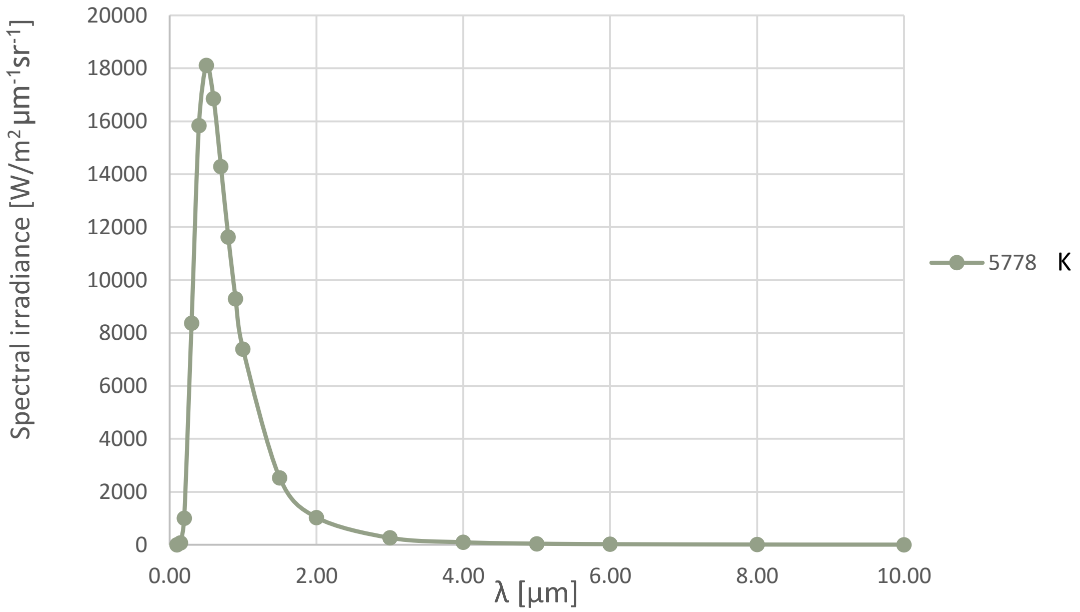
- Spectral Irradiance's SI units are W m^{-3} sr^{-1}

Efficiency

Receiver's efficiency: $Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$

- Assuming Sun's surface is at 5778K,

Sun's blackbody radiation

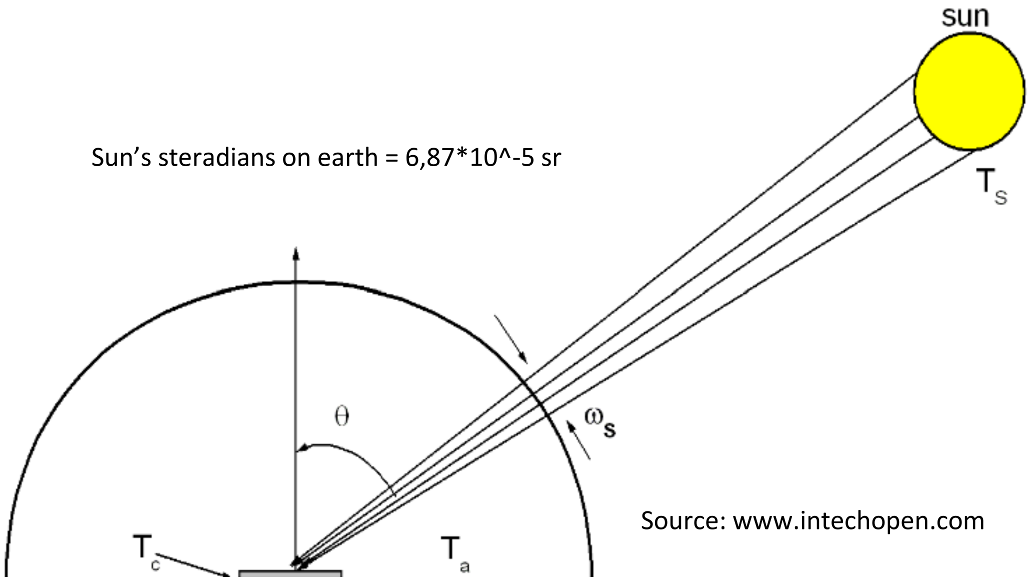


Efficiency

Receiver's efficiency: $Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$

- The units of the Planck's law are per steradian. Therefore, multiplying the Spectral Irradiance by the steradians the sun occupies in Earth's sky we will get the Irradiance in W m^{-3}

Sun's steradians on earth = 6,87*10^-5 sr

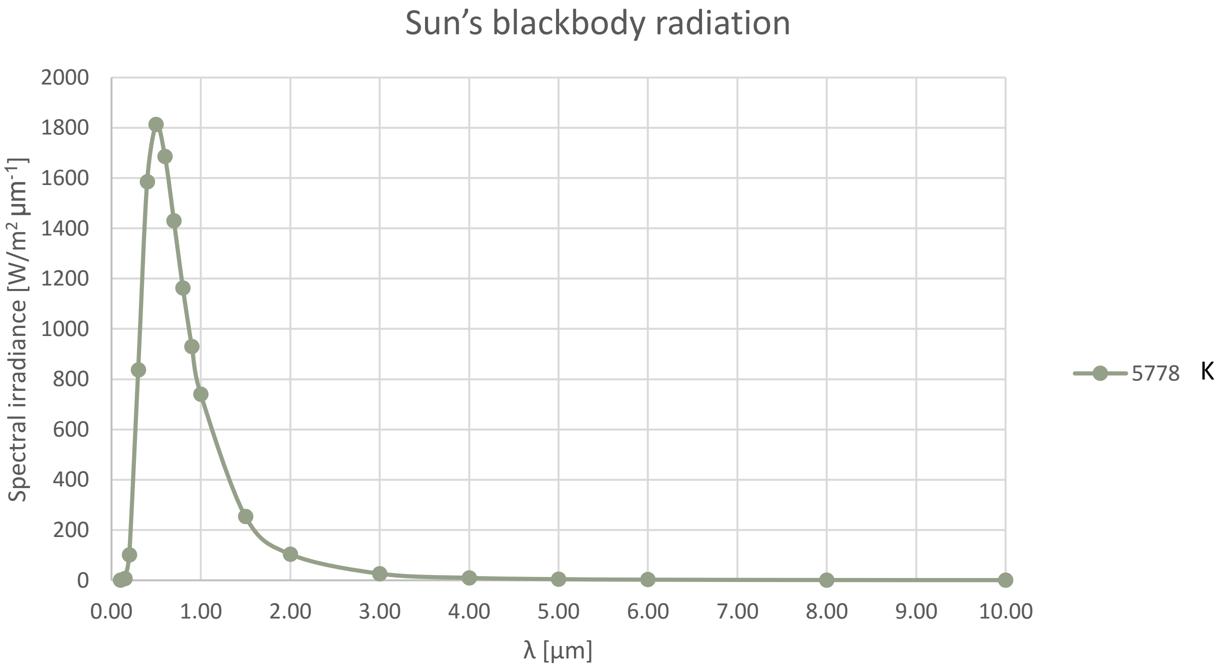


Source: www.intechopen.com

Efficiency

Receiver's efficiency: $Q_{solar} = \eta_{optics} \cdot C \cdot A \cdot I$

- Therefore, we get new values for the Irradiance



Efficiency

Receiver's efficiency: $Q_{absorbed}$

- $Q_{absorbed}$ is the ammount of radiation absorbed by the receiver on top of the tower, and is defined as follows:

$$Q_{absorbed} = \alpha \cdot Q_{solar}$$

- Where α =stands for absorptivity

Efficiency

Receiver’s efficiency: Q_{lost}

- Q_{lost} is the ammount of radiation lost due to emissions in the IR spectra of the receiver, it is defined as:

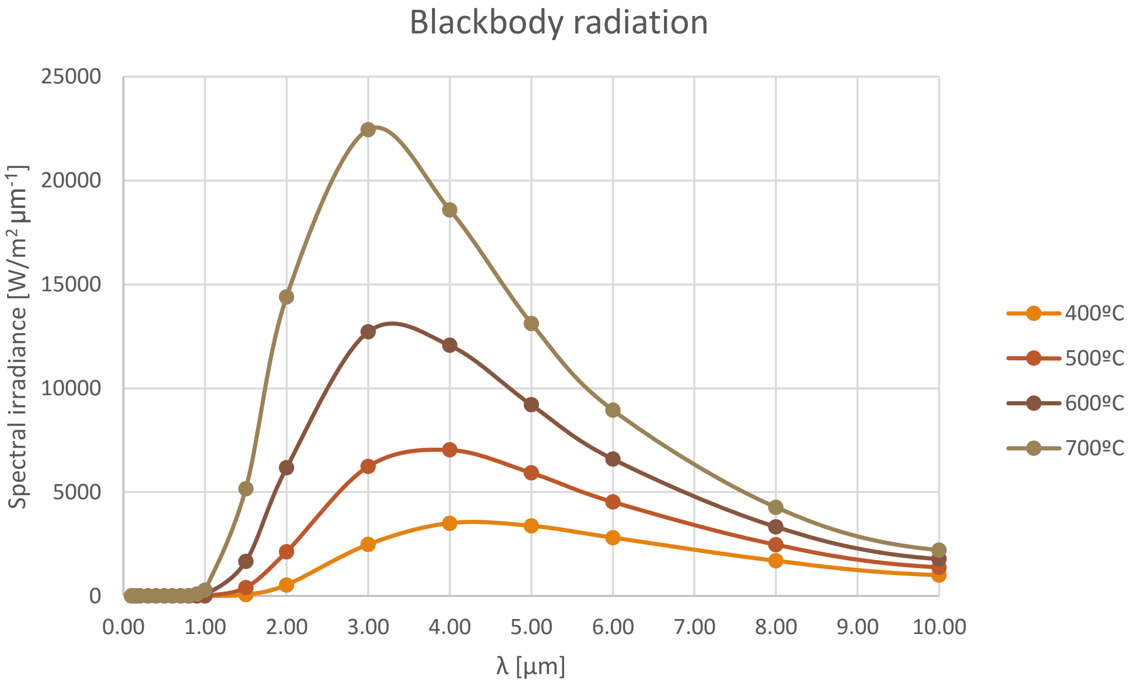
$$Q_{lost} = \mathrm{A}\cdot\varepsilon\cdot\sigma\cdot T_H^4$$

- Where A = Receiver’s area, ε is the surface’s emissivity, σ stands for Steffan-Boltzmann constant andT_H = Receiver’s surface temperature

Efficiency

Receiver's efficiency: $Q_{lost} = \text{A}\cdot\varepsilon\cdot\sigma\cdot T_H^4$

- If Q_{lost} is plotted per unit of area and assuming ε=1 to show blackbody radiation of different temperatures



Efficiency

Total efficiency:

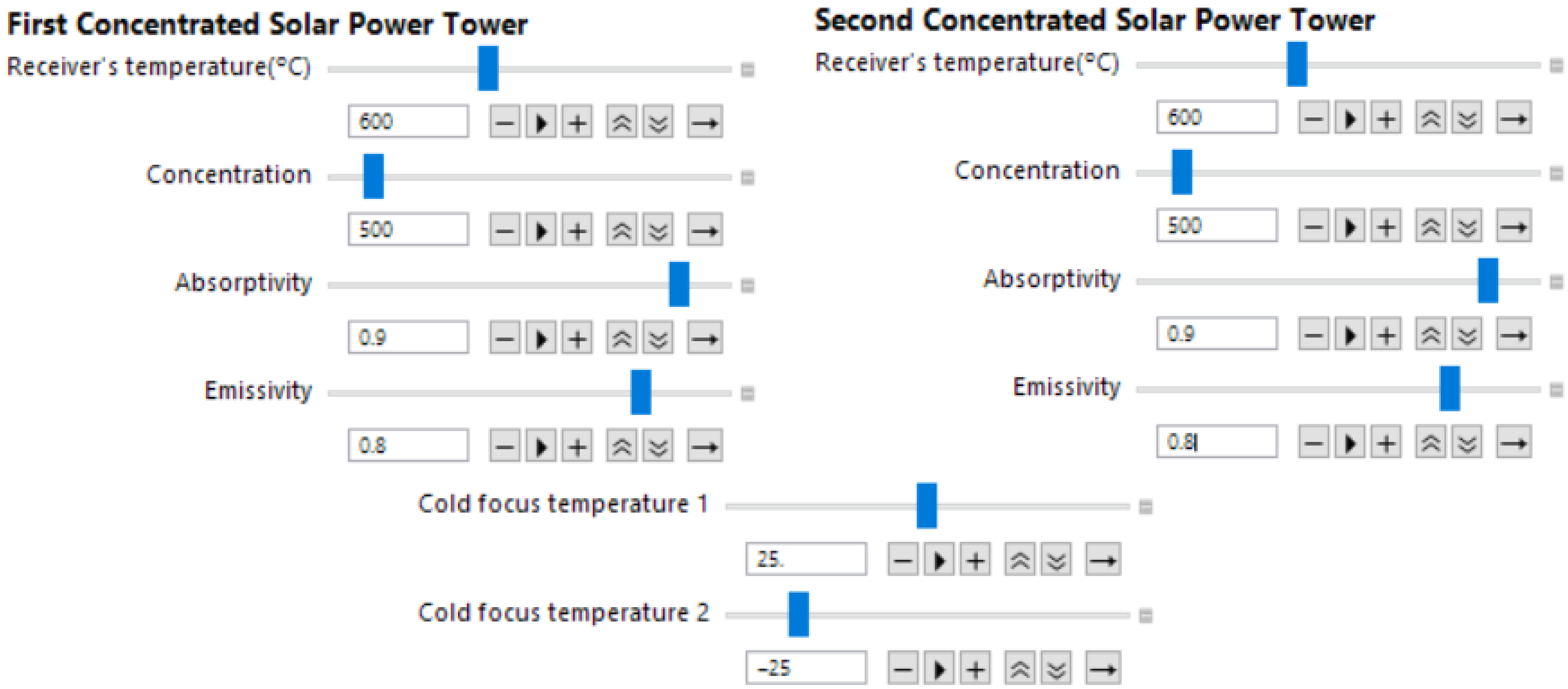
- The total efficiency is therefore defined as the product of receiver’s and carnot’s efficiencies.

$$\eta_{Receiver} = \frac{Q_{absorbed} - Q_{\ lost}}{Q_{solar}} \qquad \eta_{th} \le 1 - \frac{T_C}{T_H}$$

- Then, $\eta_{\text{total}} = \frac{Q_{absorbed} - Q_{\ lost}}{Q_{solar}} \left(1 - \frac{T_C}{T_H}\right) = \frac{\alpha \cdot C \cdot I - \varepsilon \cdot \sigma \cdot T_H^4}{C \cdot I} \left(1 - \frac{T_C}{T_H}\right)$

Efficiency

- Using Wolfram Mathematica, a computational model has been created to actively show how every variable affects efficiency



First Concentrated Solar Power Tower

Receiver's temperature(°C) 600

Concentration 500

Absorptivity 0.9

Emissivity 0.8

Second Concentrated Solar Power Tower

Receiver's temperature(°C) 600

Concentration 500

Absorptivity 0.9

Emissivity 0.8

Cold focus temperature 1 25.

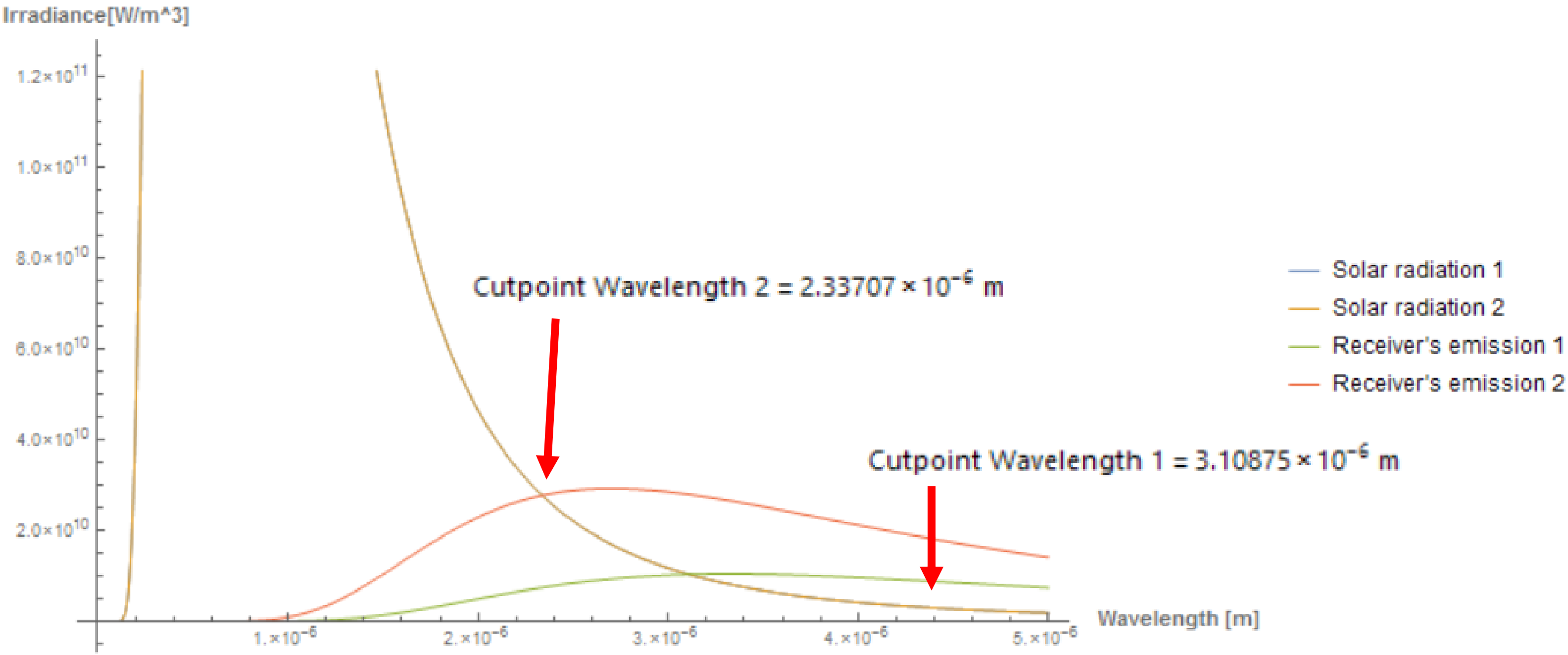
Cold focus temperature 2 -25

Efficiency

- In the following slides different situations will be shown with only one variable changed
- This way, how each one of the variables affect efficiency will be clearly detected
- Real-world experience of CSP reveals that there exists a 25-60 percent shortfall in projected production, so the following numbers and graph are theoretically correct but might not represent real CSP's numbers

Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	800	500	0.8	0.9	25

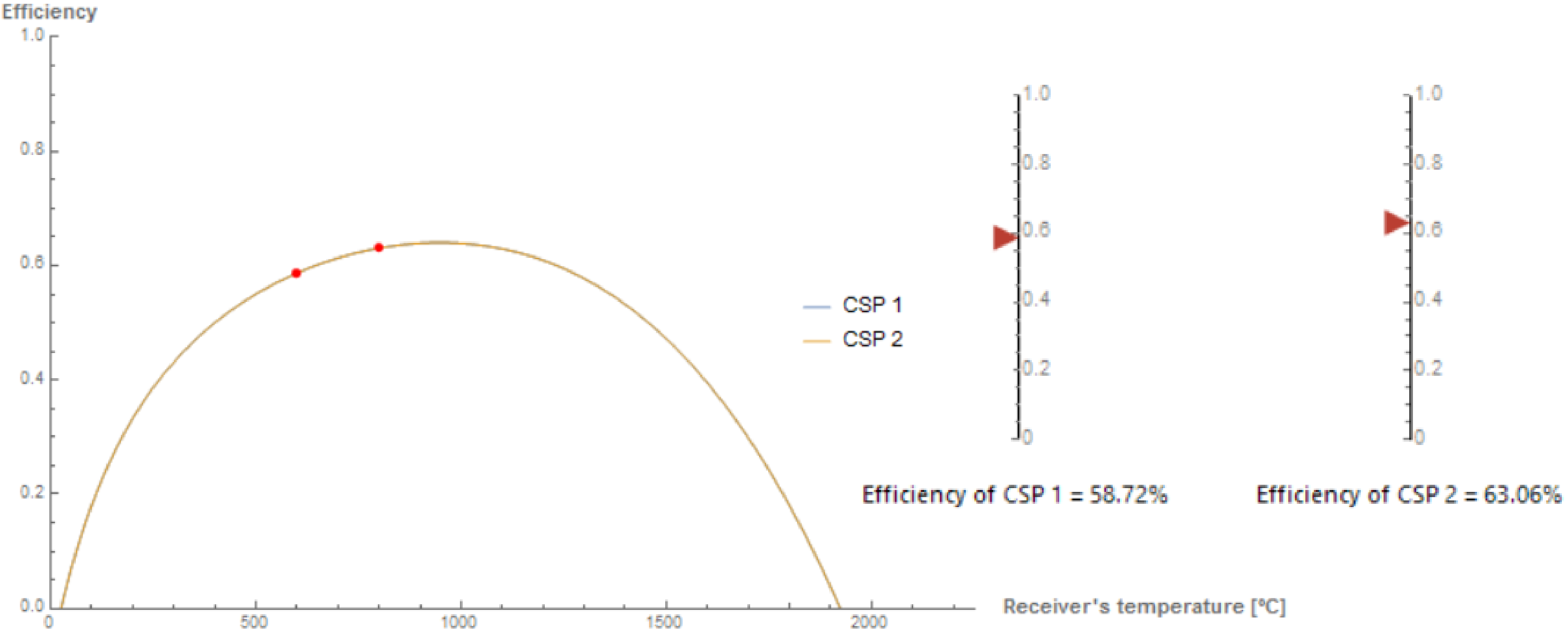


Cutpoint Wavelength 2 = 2.33707×10^{-6} m

Cutpoint Wavelength 1 = 3.10875×10^{-6} m

Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	800	500	0.8	0.9	25

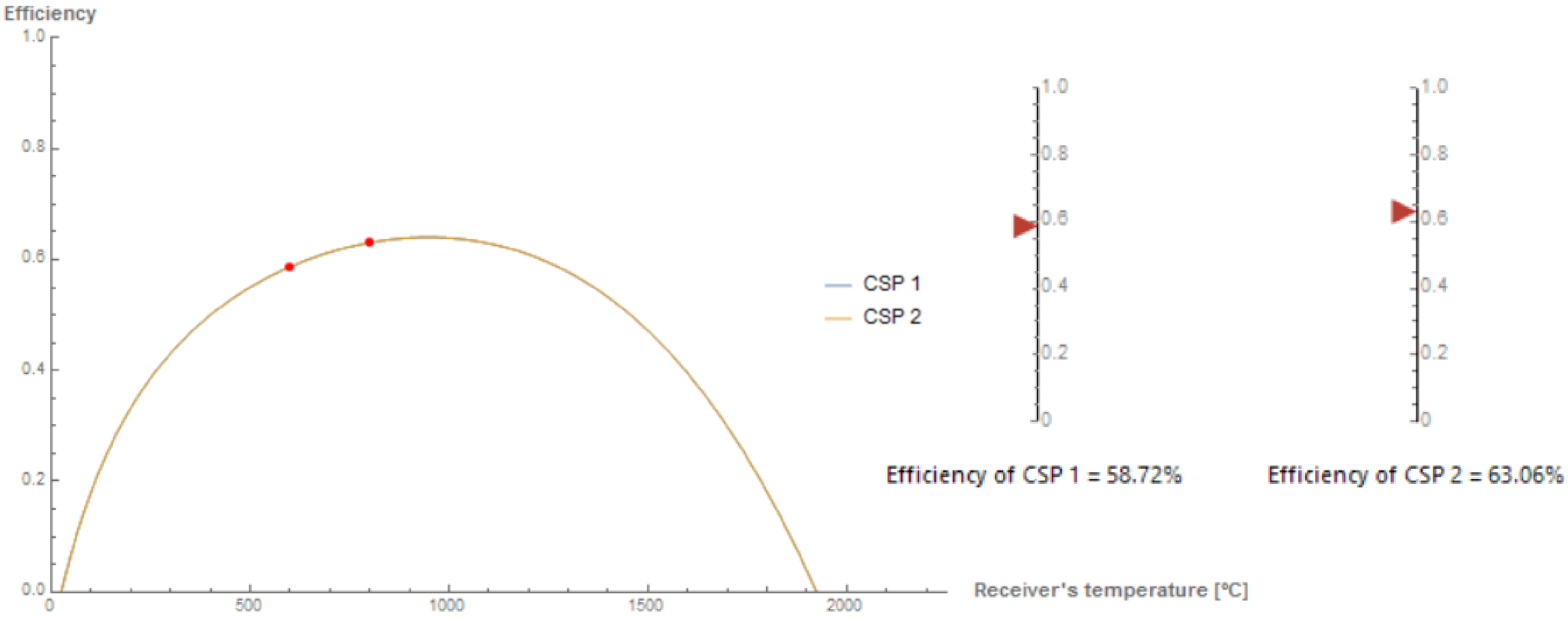


Efficiency of CSP 1 = 58.72%

Efficiency of CSP 2 = 63.06%

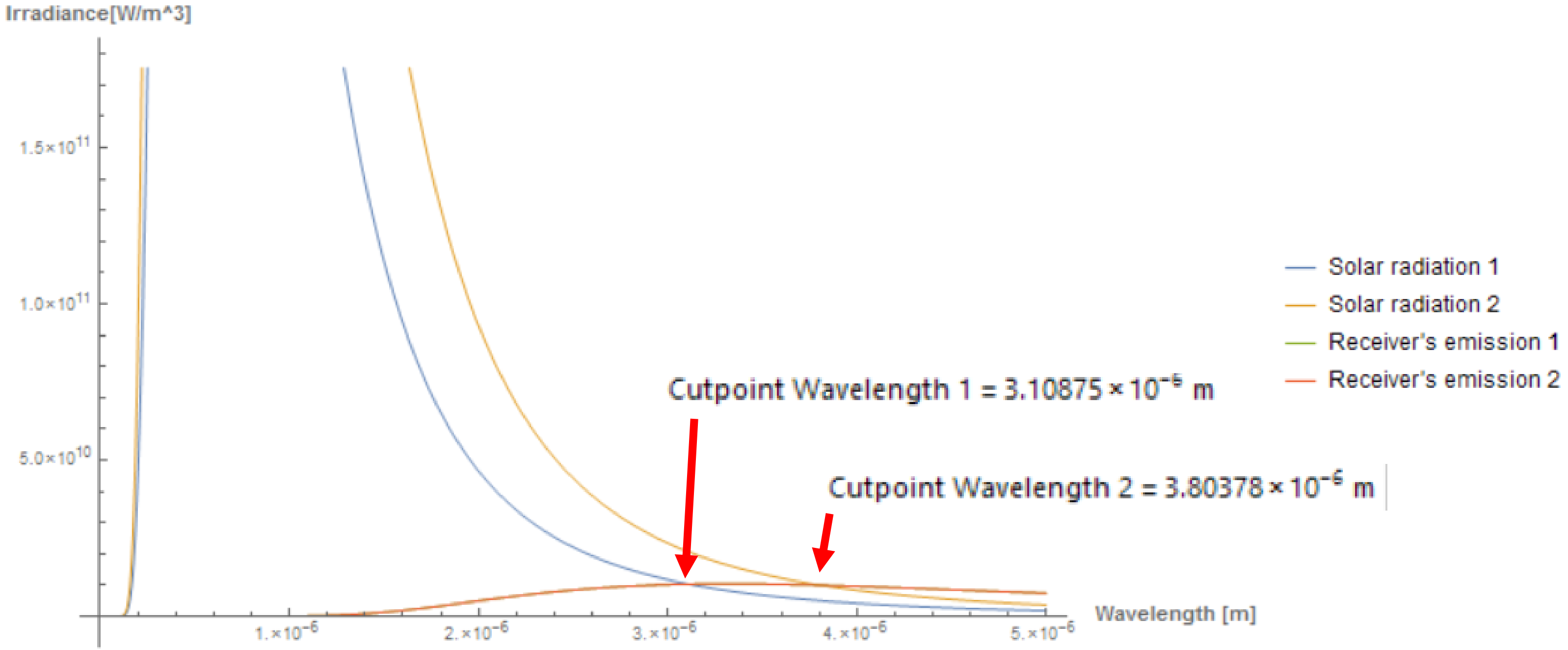
Efficiency

- The curve shows that there is a temperature for a maximum efficiency. In this case, raising temperature did not make the CSP move beyond that point and so overall efficiency goes up as IR emissions are less relevant than Carnot's efficiency and absorbed energy together.



Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	1000	0.8	0.9	25

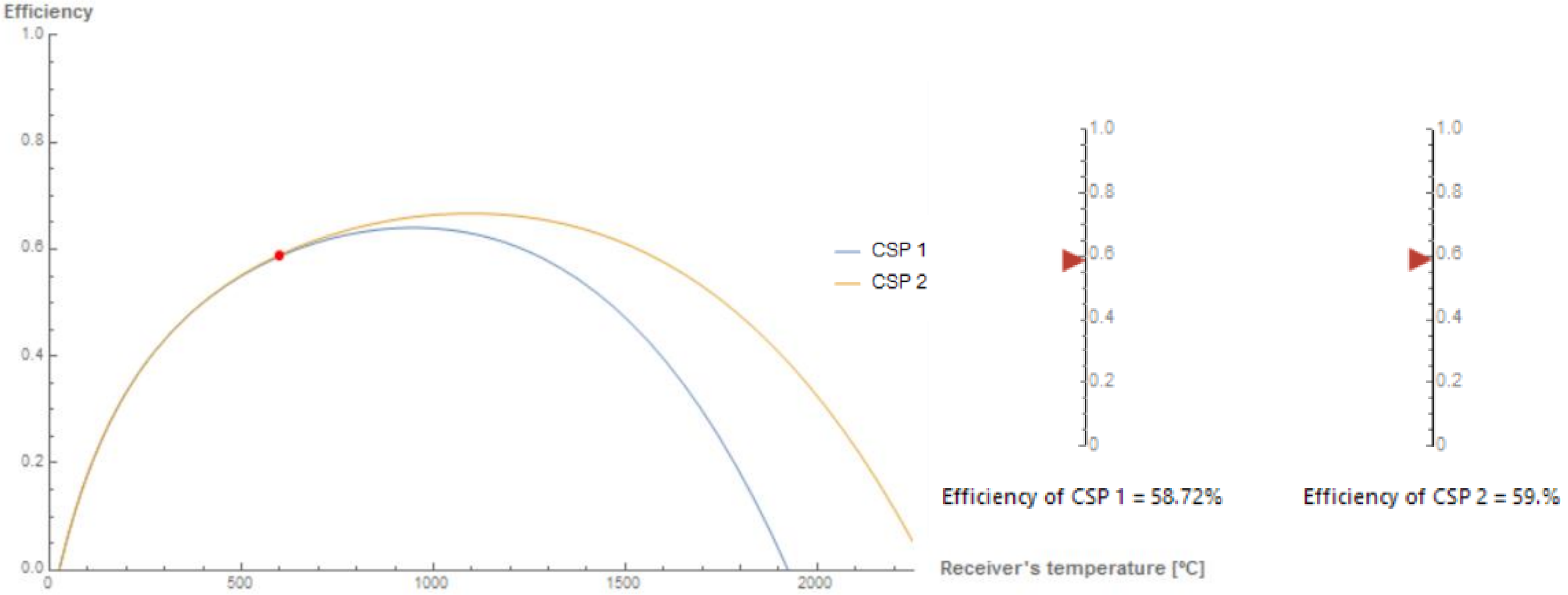


Cutpoint Wavelength 1 = 3.10875×10^{-6} m

Cutpoint Wavelength 2 = 3.80378×10^{-6} m

Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	1000	0.8	0.9	25

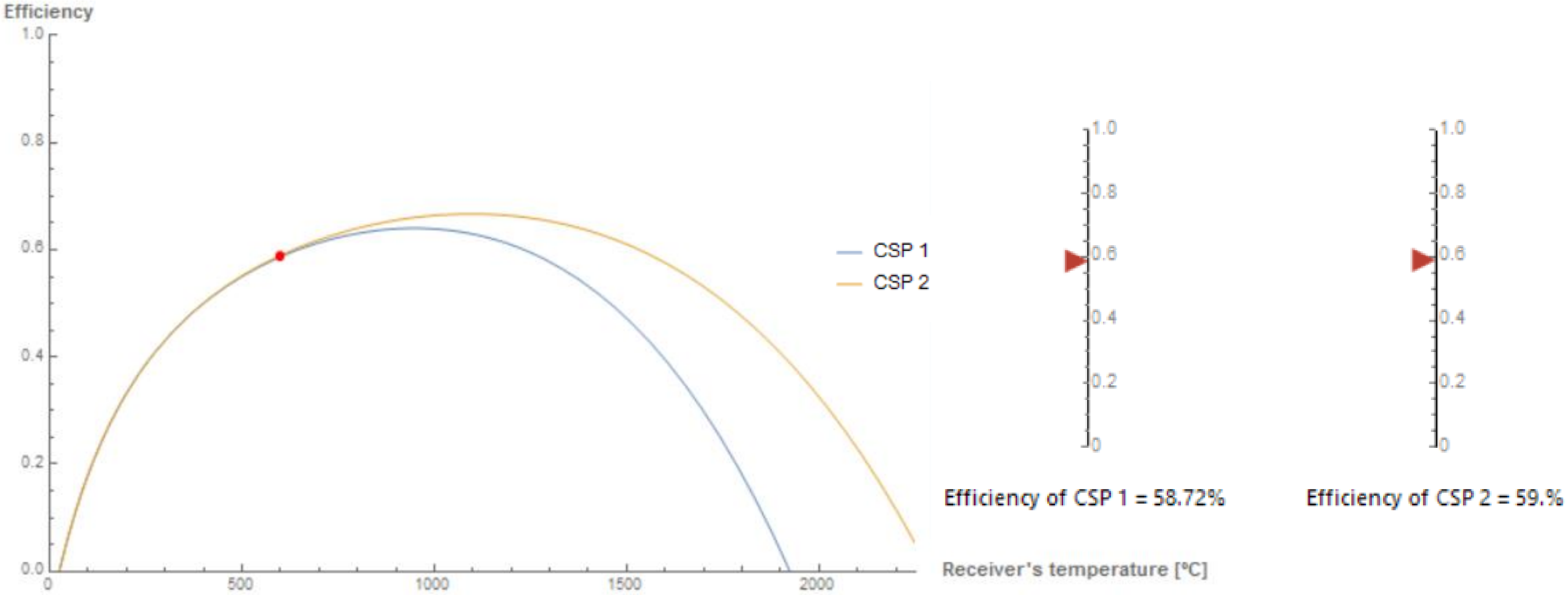


Efficiency of CSP 1 = 58.72%

Efficiency of CSP 2 = 59.%

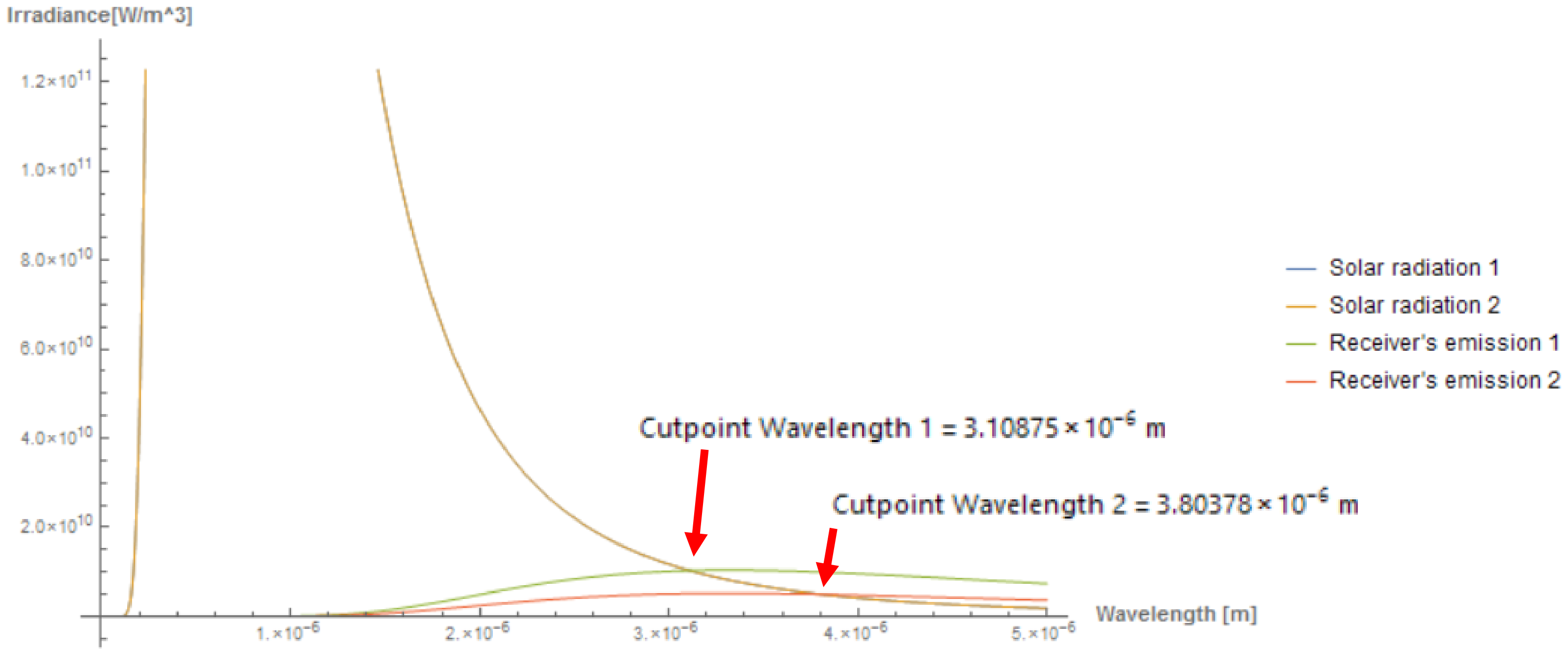
Efficiency

- Bigger concentrations move the efficiency curve upwards, as can be seen. The efficiency improvement is more noticeable at high temperatures (from the optimum temperature and on).



Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	500	0.4	0.9	25



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Efficiency

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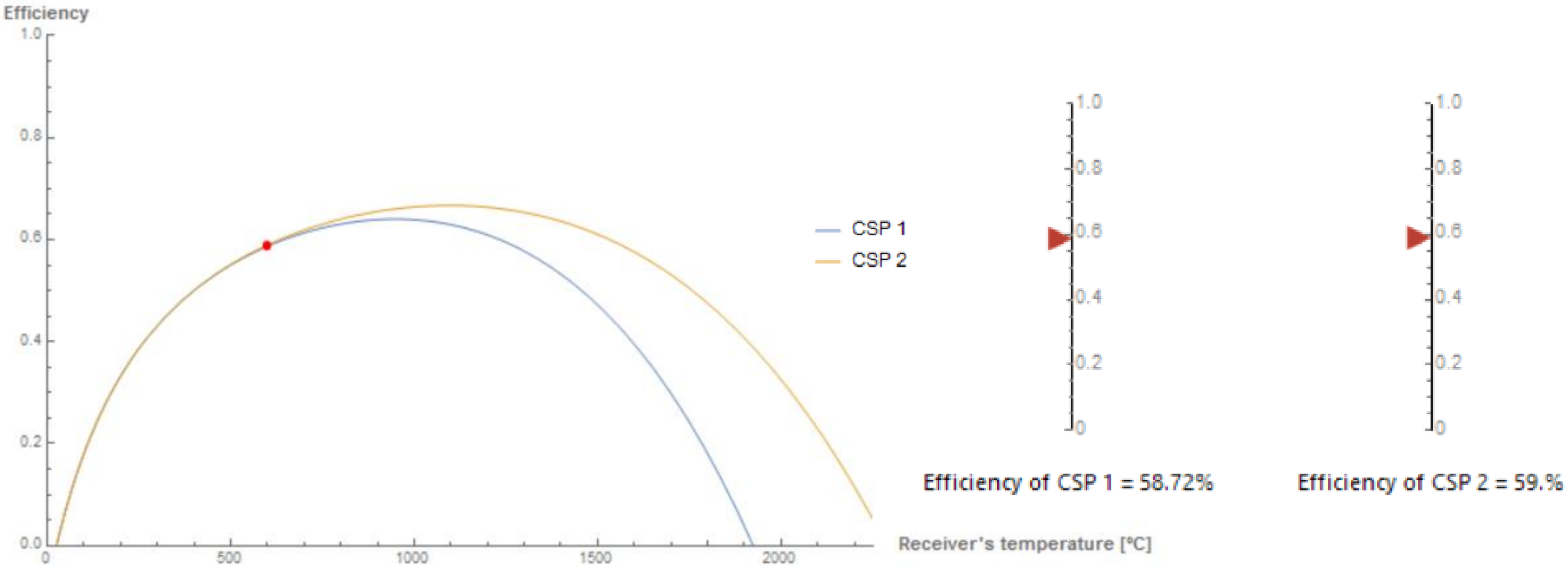
CSP 1	600	500	0.8	0.9	25
CSP 2	600	500	0.4	0.9	25

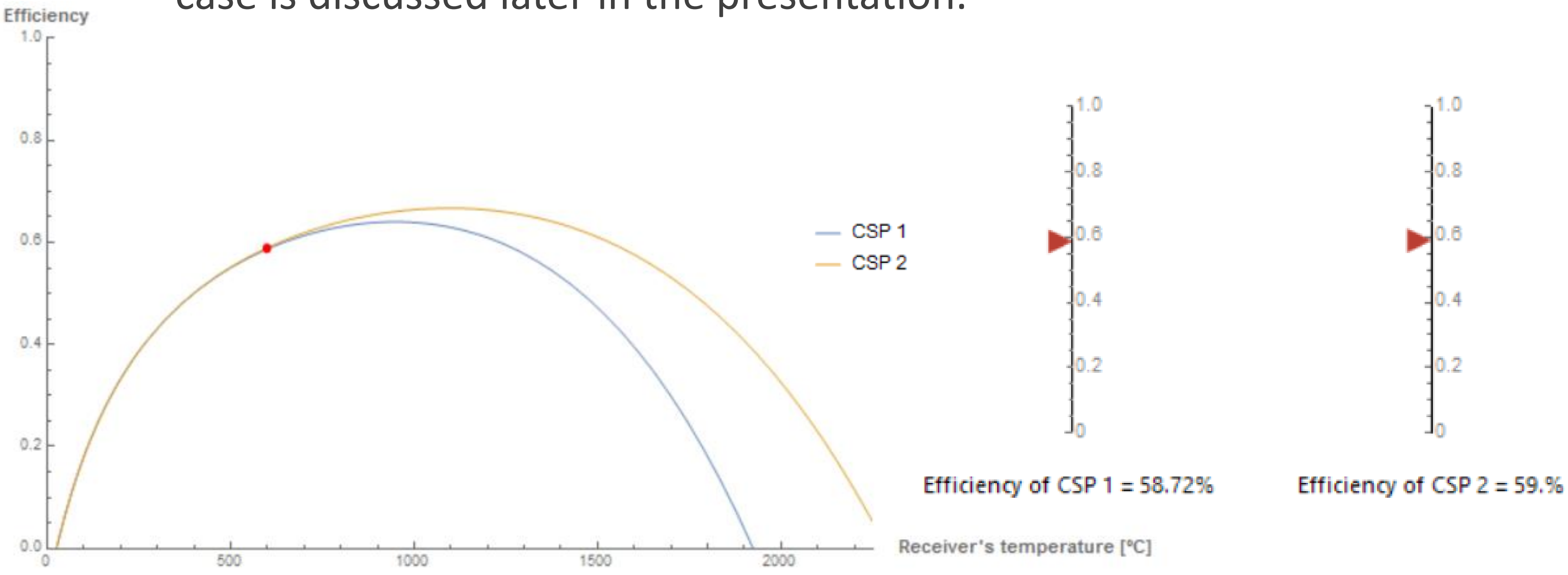


Efficiency of CSP 1 = 58.72%

Efficiency of CSP 2 = 59.%

Efficiency

- Even if it is not easy to deduce from the formula at first sight, these plots and calculations show that the effect of multiplying the concentration by 2 and using a material with half the emissivity is exactly the same (at least in terms of efficiency and cut-point). This case is discussed later in the presentation.

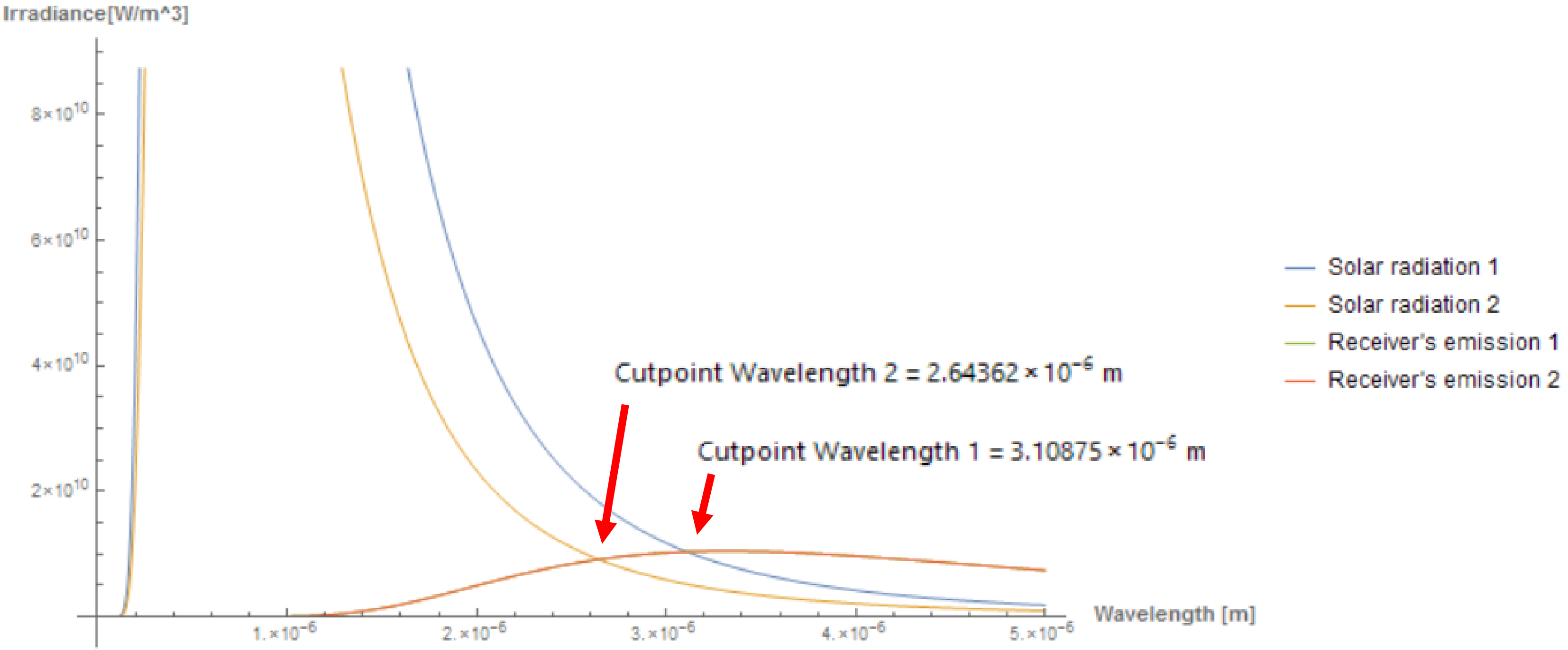


Efficiency of CSP 1 = 58.72%

Efficiency of CSP 2 = 59.%

Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	500	0.8	0.45	25

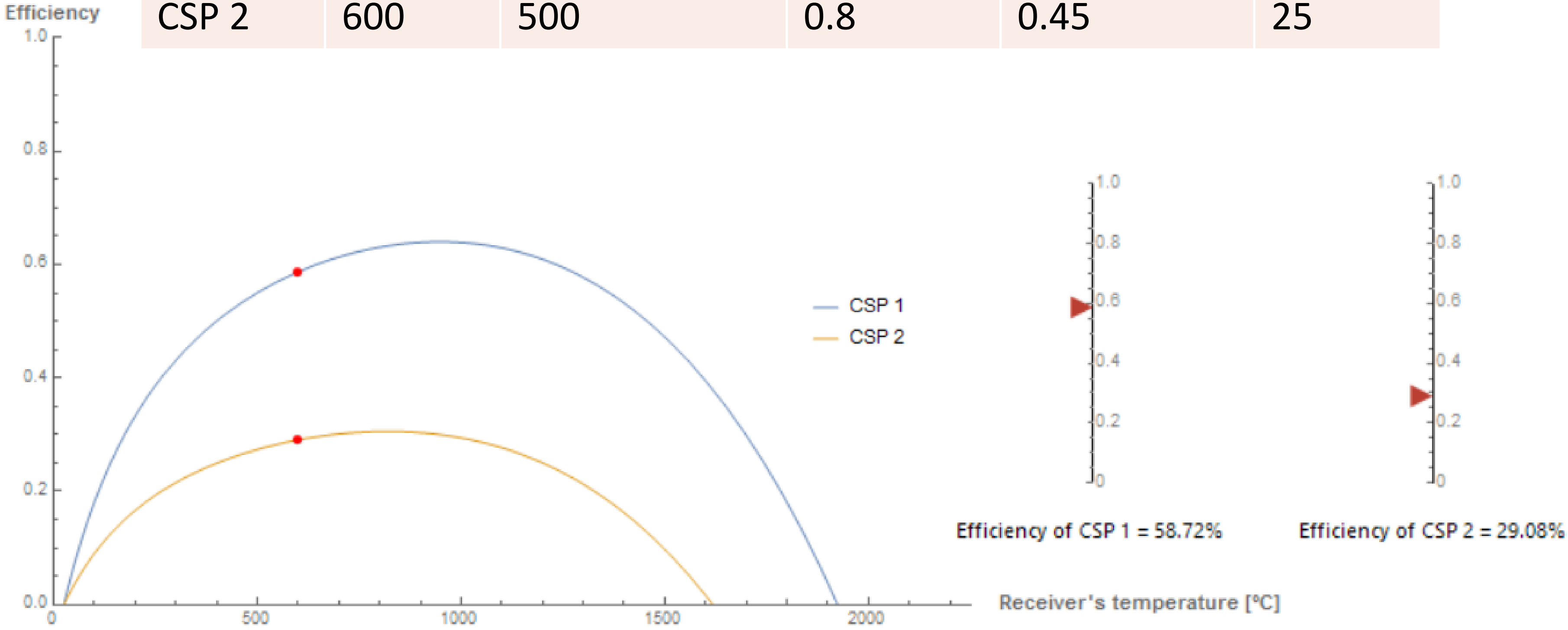


Cutpoint Wavelength 2 = 2.64362×10^{-6} m

Cutpoint Wavelength 1 = 3.10875×10^{-6} m

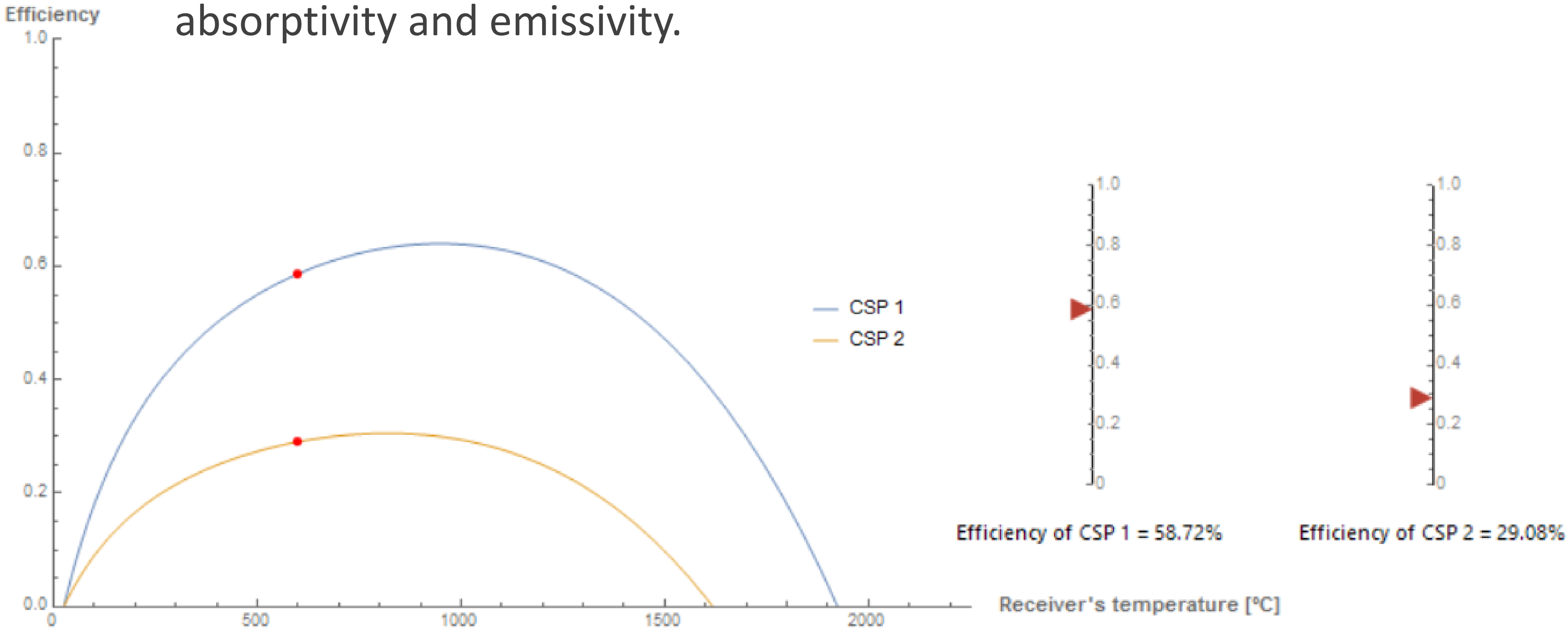
Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	500	0.8	0.45	25



Efficiency

- Reducing the absorptivity has a bigger effect than reducing the emissivity, so keeping the rest of variables constant we would prefer a surface with high absorptivity and emissivity than one with low absorptivity and emissivity.

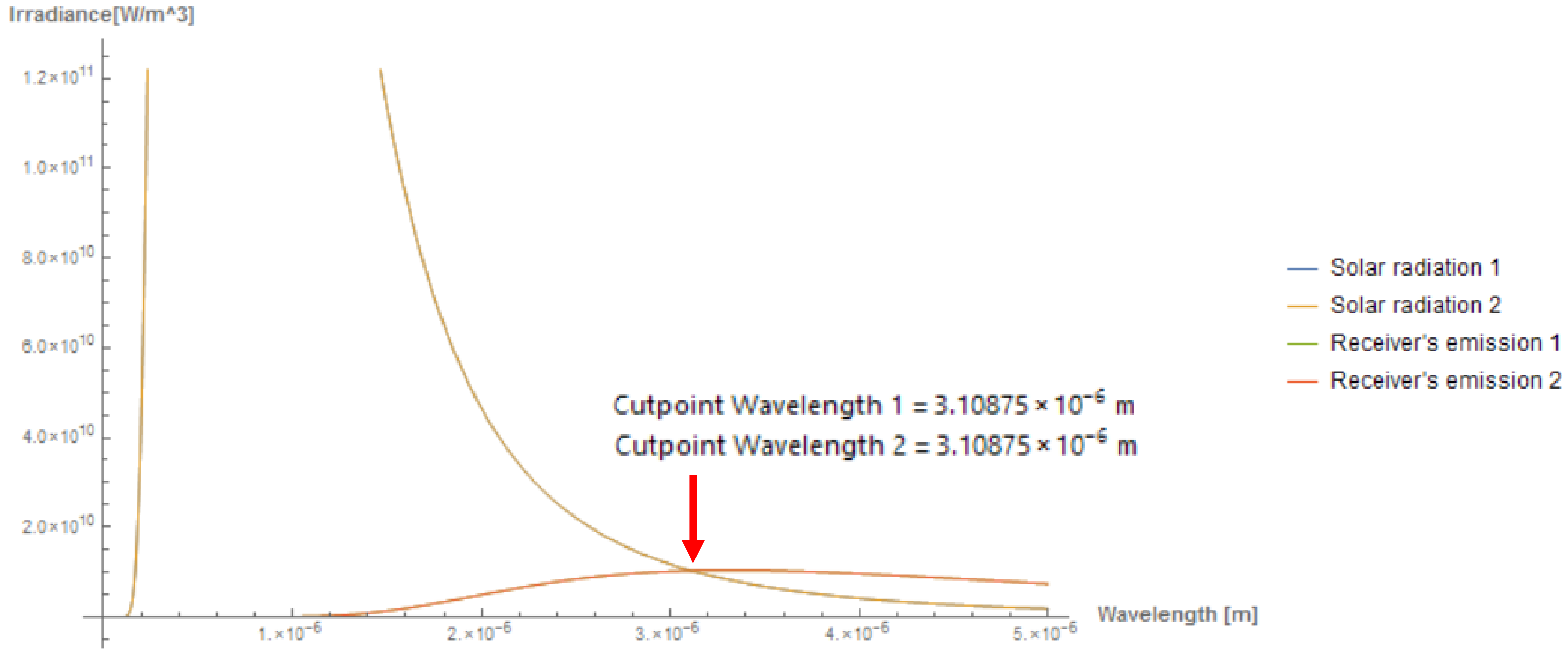


Efficiency of CSP 1 = 58.72%

Efficiency of CSP 2 = 29.08%

Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	500	0.8	0.9	-25

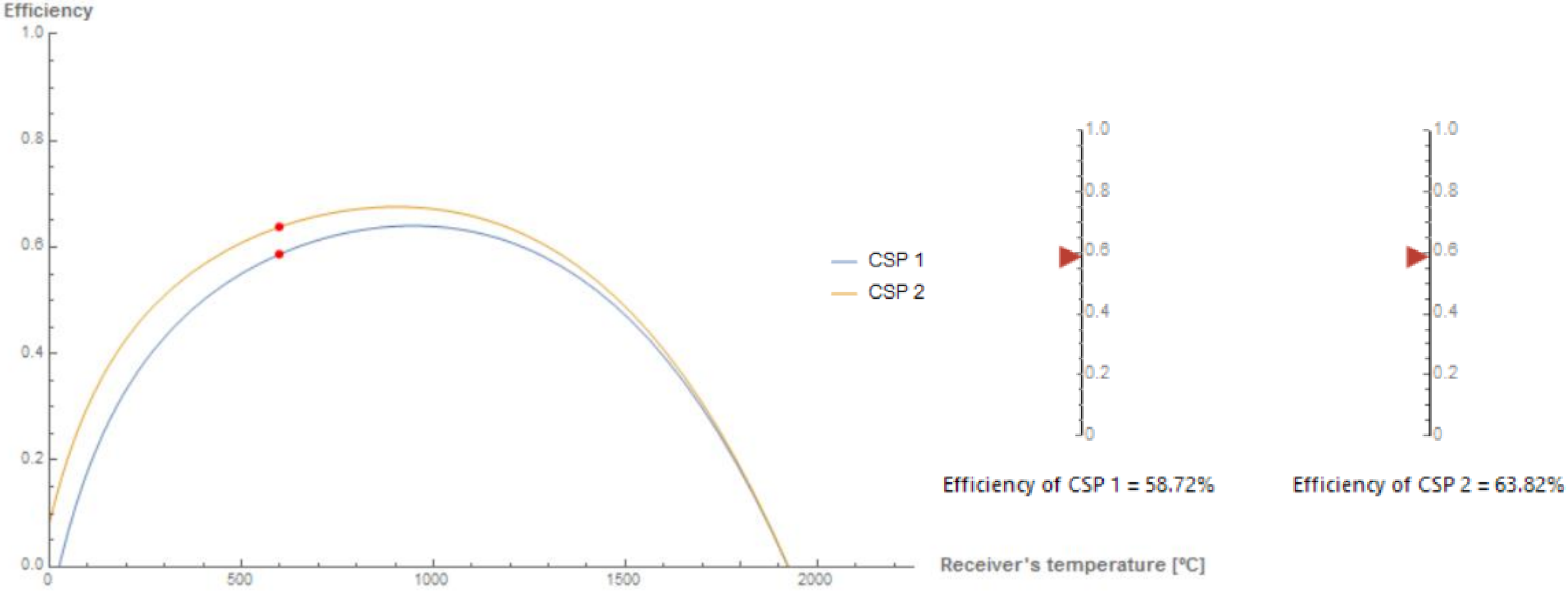


Cutpoint Wavelength 1 = 3.10875×10^{-6} m

Cutpoint Wavelength 2 = 3.10875×10^{-6} m

Efficiency

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.8	0.9	25
CSP 2	600	500	0.8	0.9	-25

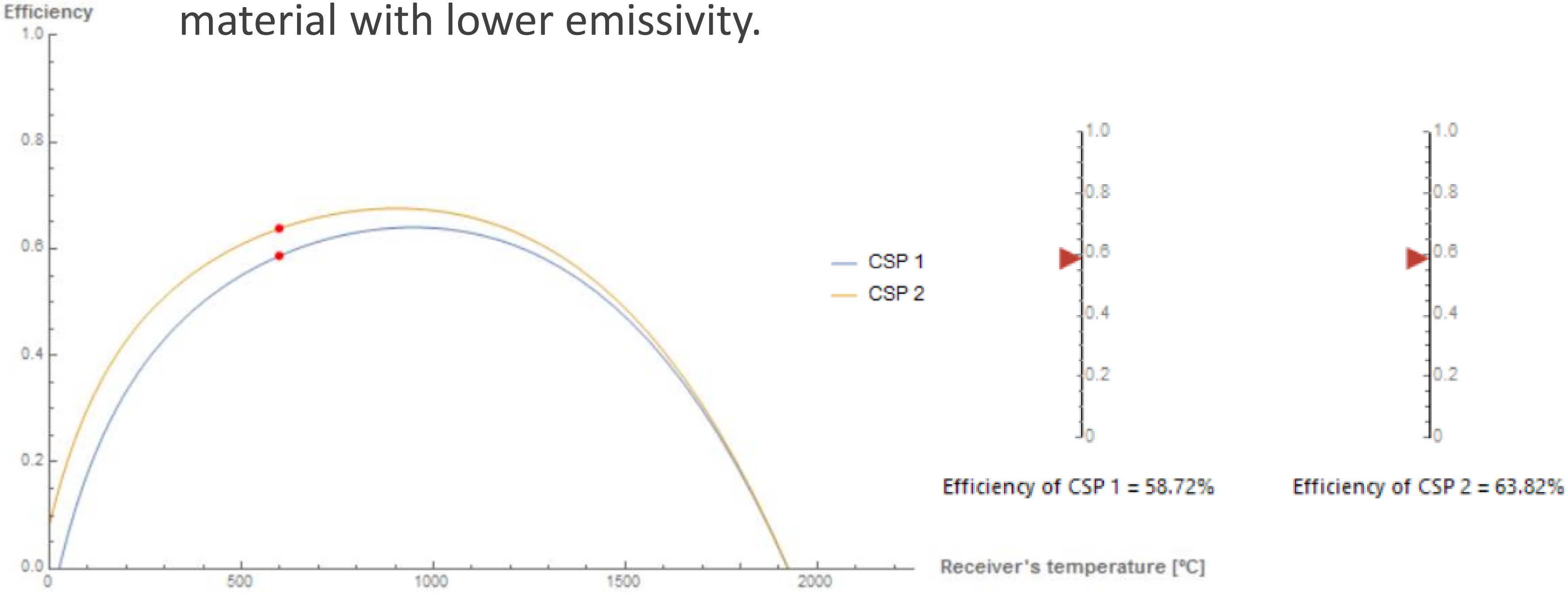


Efficiency of CSP 1 = 58.72%

Efficiency of CSP 2 = 63.82%

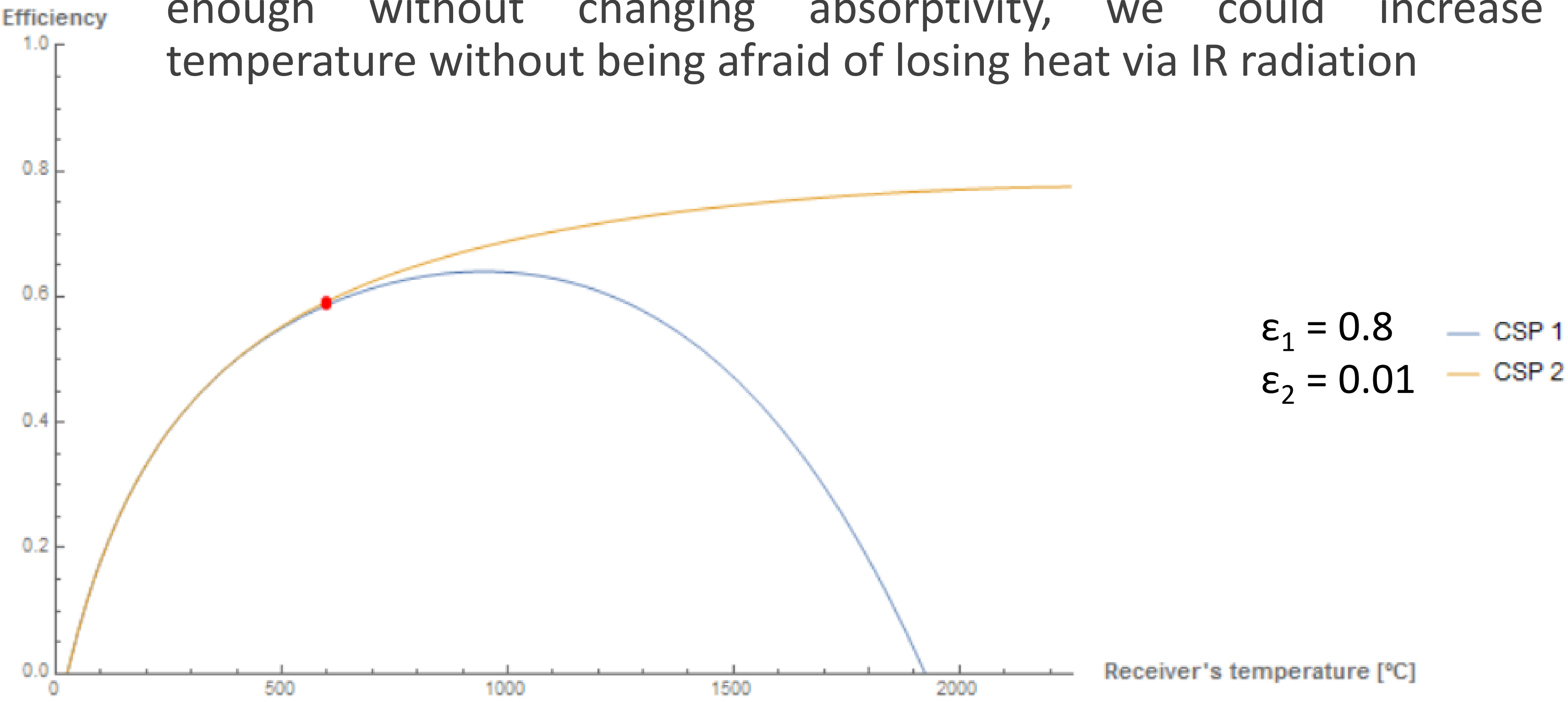
Efficiency

- Lowering the cold source's temperature seems to be as important (or even more) as lowering emissivities at low temperature CSP's. Specially because lowering the cold temperature is relatively easy (using liquid nitrogen for example) compared to developing a material with lower emissivity.



Efficiency objective

- As mentioned before, from the currently available technology, the element with more room to improve is emissivity. If we could lower it enough without changing absorptivity, we could increase temperature without being afraid of losing heat via IR radiation

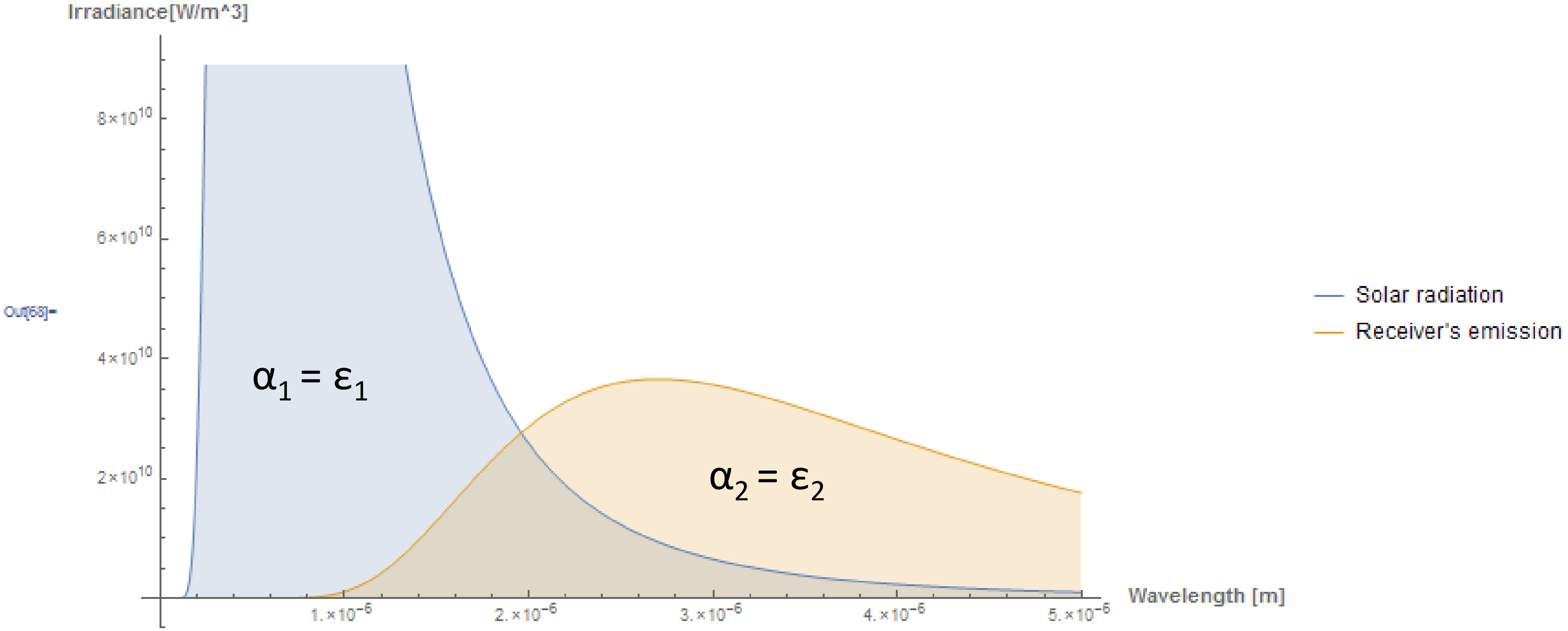


$\varepsilon_1 = 0.8$

$\varepsilon_2 = 0.01$

Efficiency objective

- However, every time absorption was being used up to this point, it was applied to the solar spectrum only, and every time emissivity was used, it was applied to the receiver's emission only, regardless of their wavelength composition.

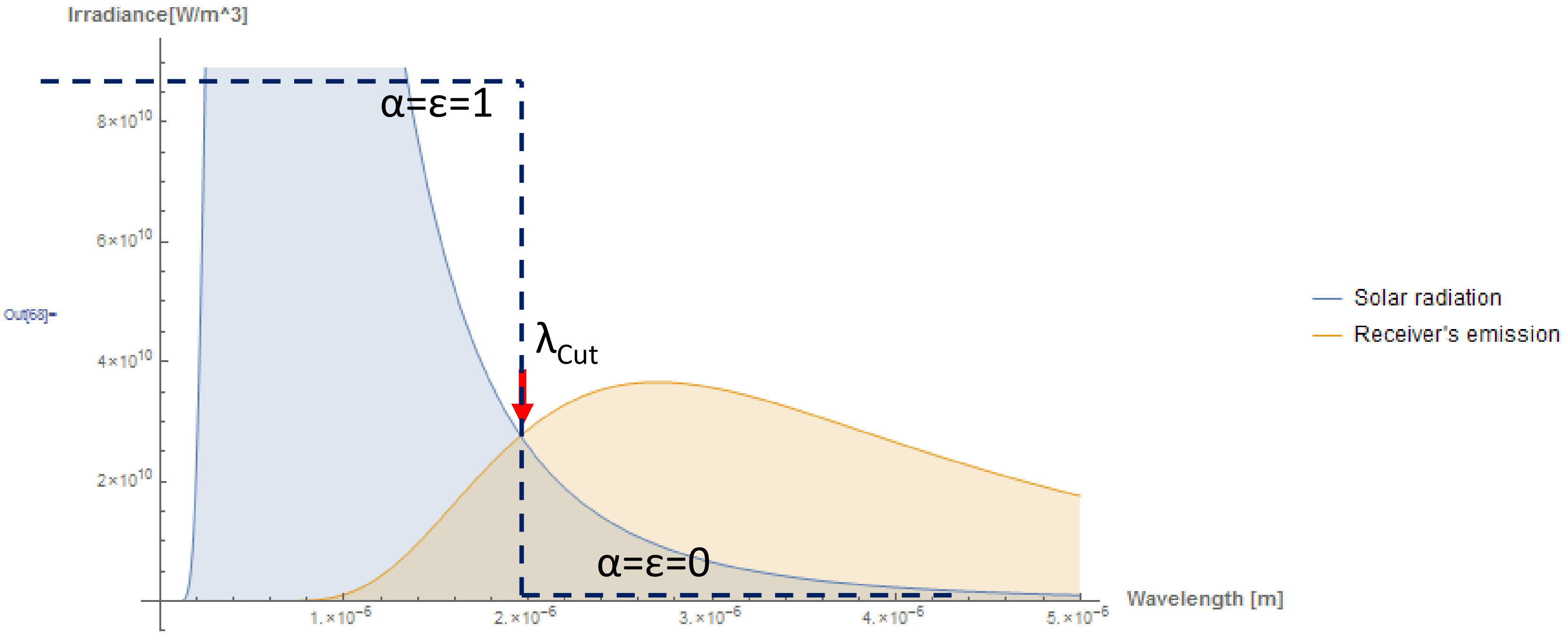


Efficiency objective

- That is how the ultimately perfect material would act. However, there is no way to design a material so that it has an absorption value for the whole solar spectrum and another value for the whole thermal emission.
- There are different ways, though, to design materials with different emissivity values for different wavelengths. So the ideal material would have an absorptivity value of 1 until the wavelength where the solar and the emission spectra cut, and a value of 0 from that point on.

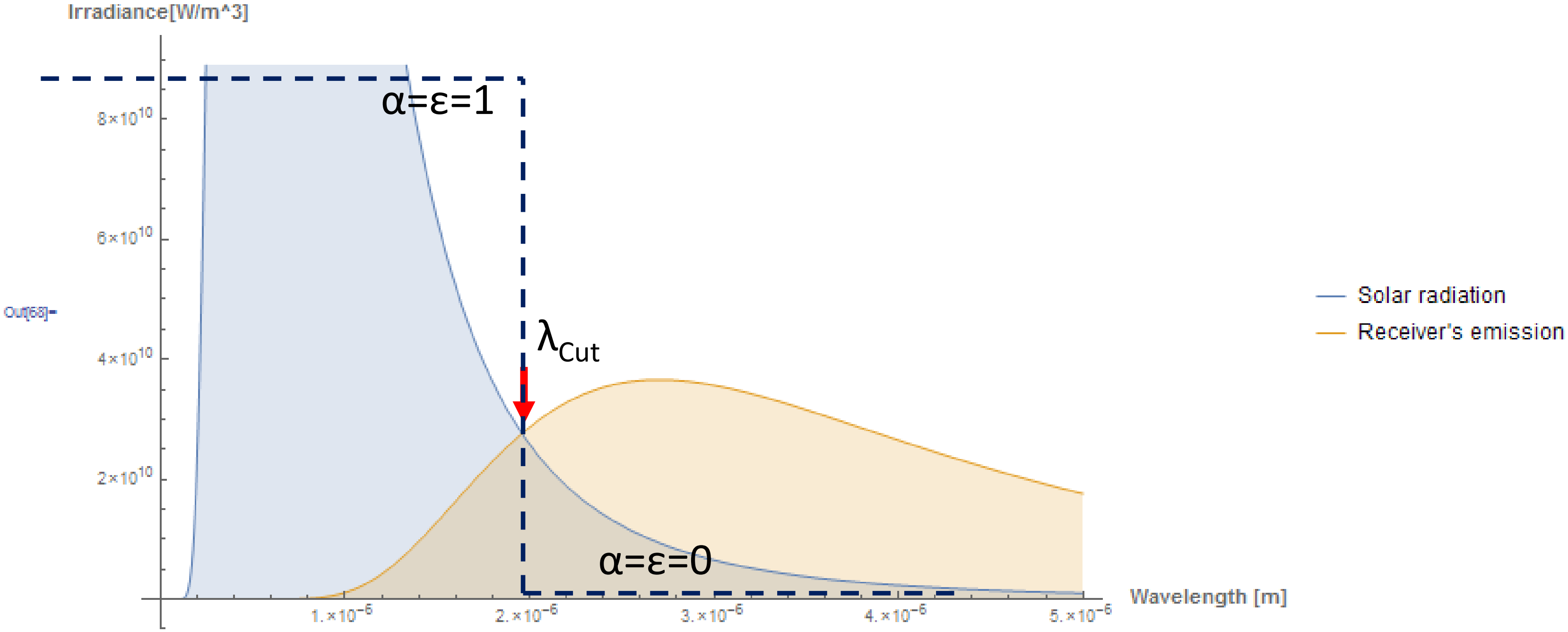
Efficiency objective

- In contrast to the previous model, blue shaded solar radiation from λ_{Cut} on would not be absorbed, and the orange shaded receiver's emission before λ_{Cut} would be irreversibly emitted.



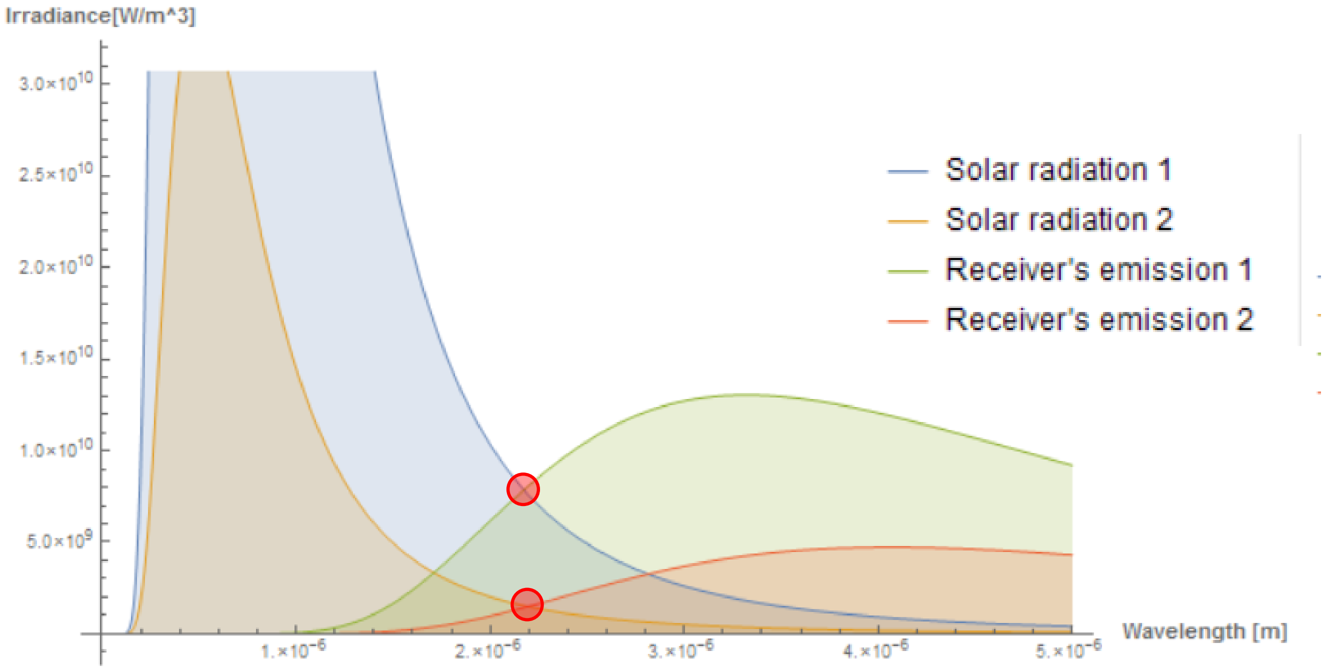
Efficiency objective

- This is in fact the big dilema of SPTs. The higher temperature the receiver works at, the more area that both curves have in common and so the more it is being not-absorbed from the sun (after λ_{Cut}) and the more it is emitted from the receiver (before λ_{Cut}).



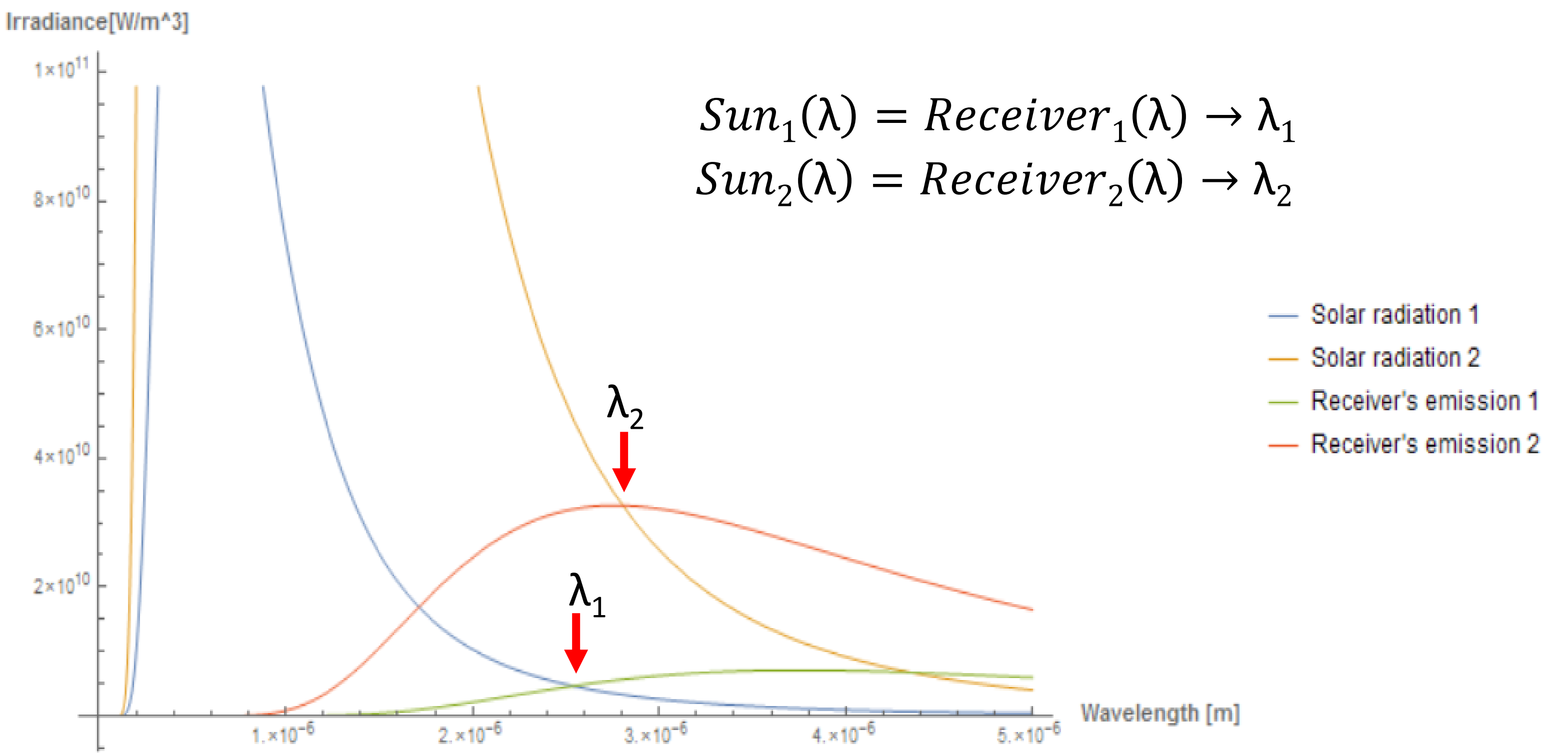
Efficiency objective

- The developed Mathematica model actively changes the Irradiance vs Wavelength graph, so two different models with different values of emissivity and absorptivity before and after the changing λ_{Cut} can be compared. The following slides are a short explanation of how it works.



Development of Mathematica Model

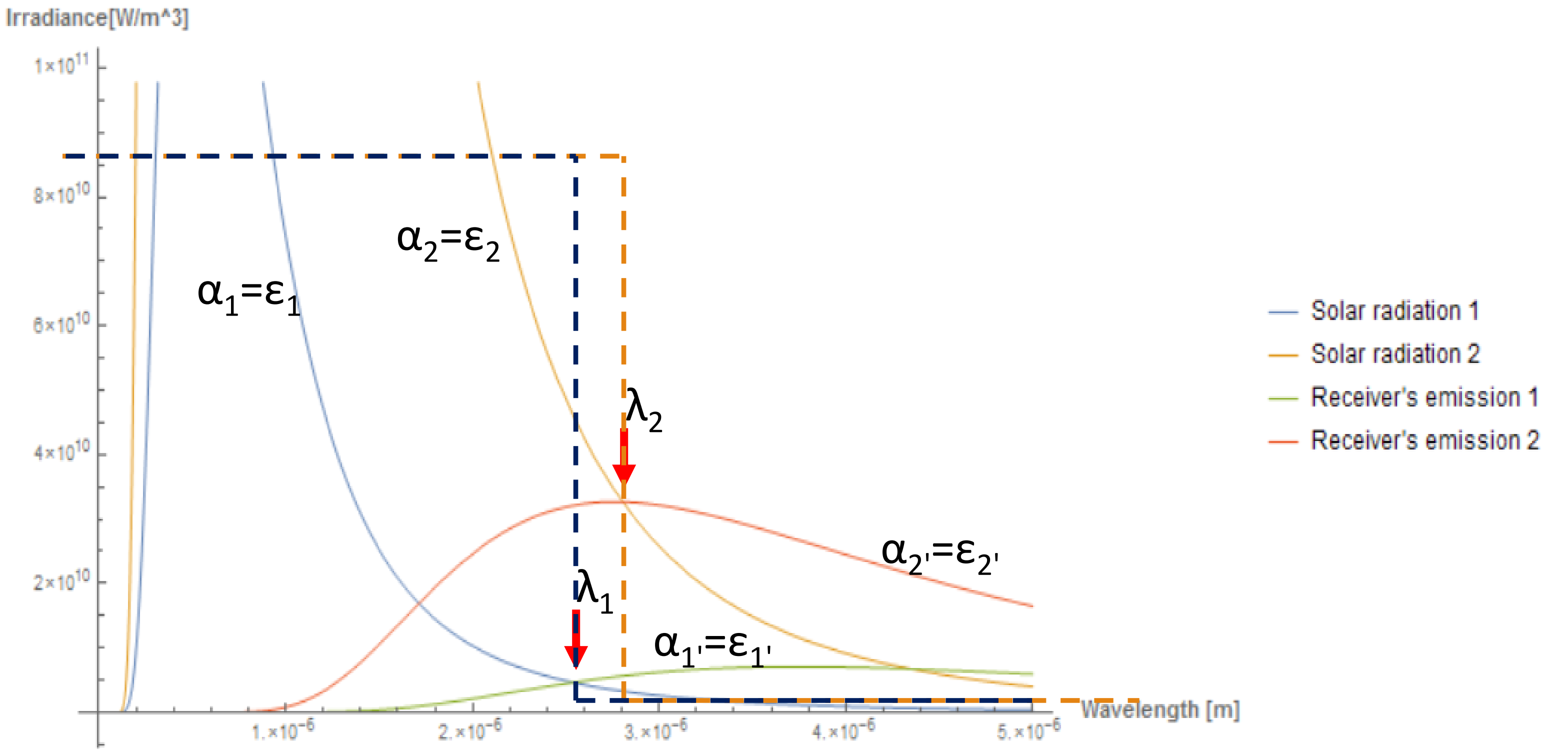
- Sun’s blackbody radiation and receiver’s emission curves are equaled and the cut-point is obtained



$$Sun_1(\lambda) = Receiver_1(\lambda) \rightarrow \lambda_1$$
$$Sun_2(\lambda) = Receiver_2(\lambda) \rightarrow \lambda_2$$

Development of Mathematica Model

- Each couple of curves has two different emissivity values (that the user can choose), one for after and one for before each of the λ_{Cut}

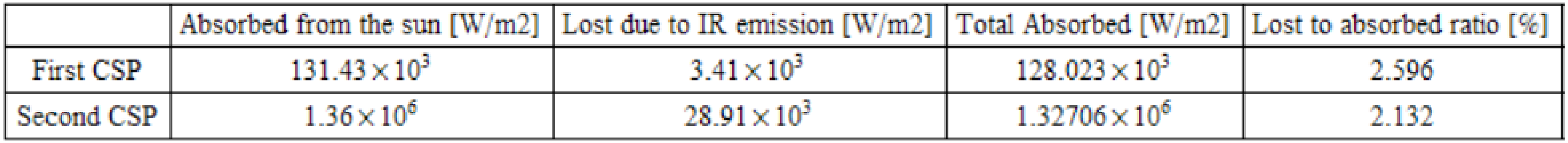


Development of Mathematica Model

- Different values have been calculated for the variable values the user decided

- “Absorbed from the Sun” is the amount of radiation that the receiver absorbs, and is calculated as $\int_0^{\lambda_{\mathrm{Cut}}} Sun_1(\lambda) \cdot \alpha_1 \, d\lambda$ [W/m²]

- “Lost due to IR emission” is the amount of radiation the receiver emits in the wavelengths smaller than λ_{Cut}. It is calculated as $\int_0^{\lambda_{\mathrm{Cut}}} Receiver_1(\lambda) \cdot \alpha_1 \, d\lambda$ [W/m²]

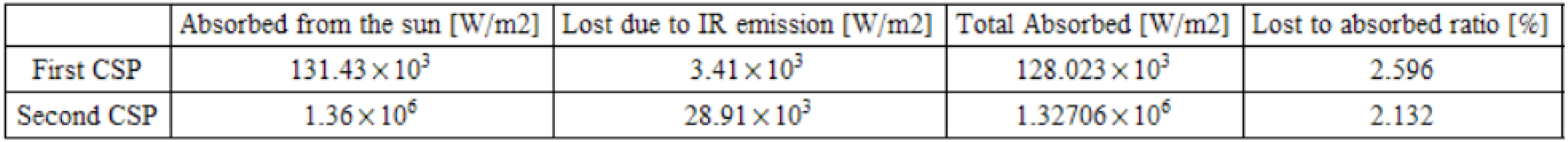


	Absorbed from the sun [W/m2]	Lost due to IR emission [W/m2]	Total Absorbed [W/m2]	Lost to absorbed ratio [%]
First CSP	131.43×10^3	3.41×10^3	128.023×10^3	2.596
Second CSP	1.36×10^6	28.91×10^3	1.32706×10^6	2.132

Development of Mathematica Model

- “Total absorbed” stands for the total amount of radiation the receiver absorbed minus that it emitted. It is obtaines as follows: $\int_0^{\lambda_{\text{Cut}}} Sun_1(\lambda) \cdot \alpha_1 \, d\lambda - \int_0^{\lambda_{\text{Cut}}} Receiver_1(\lambda) \cdot \alpha_1 \, d\lambda \; [\mathrm{W/m^2}]$

- “Lost to absorbed Ratio” shows the ratio of the radiation lost to that being absorbed in the receiver. It is calculated with the following formula: $\frac{\text{Lost due to IR emission}}{\text{Absorbed from the Sun}} \cdot 100 \; [\%]$



	Absorbed from the sun [W/m2]	Lost due to IR emission [W/m2]	Total Absorbed [W/m2]	Lost to absorbed ratio [%]
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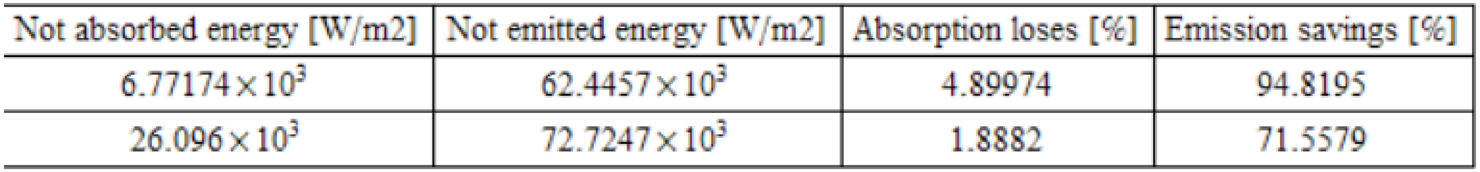
Second CSP	1.36×10^6	28.91×10^3	1.32706×10^6	2.132

Development of Mathematica Model

- “Not absorbed energy” is the amount of energy that is not being absorbed due to the emissivity change at λ_{Cut}. Its value is $\int_{\lambda_{\text{Cut}}}^{\infty} Sun_1(\lambda) \cdot \varepsilon_1 \, d\lambda$ [W/m^2]

- “Not emitted energy” is the energy that it is not emitted due to the IR emission of the receiver. It is obtained as $\int_{\lambda_{\text{Cut}}}^{\infty} Receiver_1(\lambda) \cdot \varepsilon_1 \, d\lambda$ [W/m^2]



Not absorbed energy [W/m2]	Not emitted energy [W/m2]	Absorption loses [%]	Emission savings [%]
6.77174×10^3	62.4457×10^3	4.89974	94.8195
26.096×10^3	72.7247×10^3	1.8882	71.5579

Development of Mathematica Model

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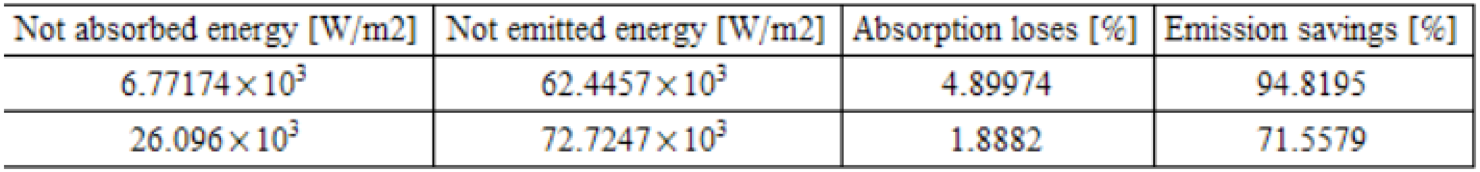
- The “Absorption loses” define the ratio between the sun’s not-absorbed energy from λ_{Cut} to the total solar energy (absorbed and not absorbed). It is calculated with the formula below:

$$\frac{\text{Not absorbed energy}}{\text{Absorbed from the Sun + Not absorbed energy}} \cdot 100[\%]$$

- The “Emission savings” define the ratio between the not-emitted receiver’s IR emission and the total IR emission of the receiver at the working temperature. It is calculated with the formula below:

$$\frac{\text{Not emitted energy}}{\text{Lost due to IR emission + Not emitted energy}} \cdot 100[\%]$$



Not absorbed energy [W/m2]	Not emitted energy [W/m2]	Absorption loses [%]	Emission savings [%]
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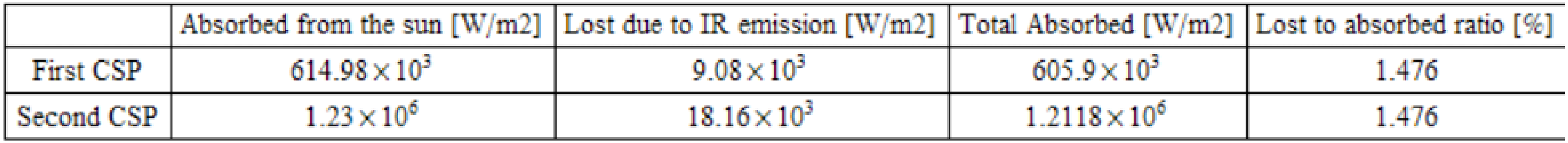
26.096×10^3	72.7247×10^3	1.8882	71.5579

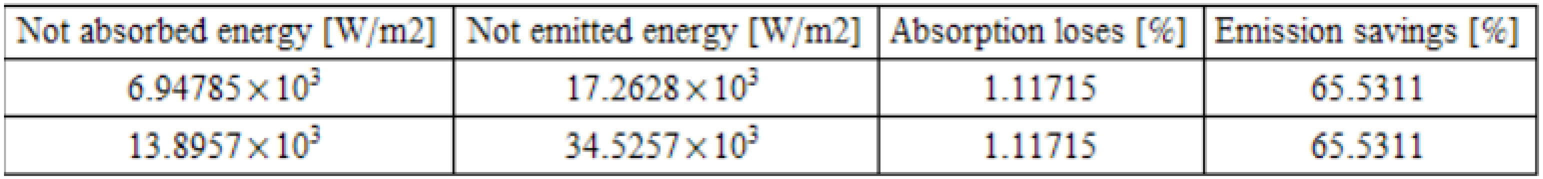
Development of Mathematica Model

- To show an example of its usefulness, the example discussed before were CSP1 has half the emissivity of CSP2 and CSP2 has twice the concentration that of CSP1 has been used. In the plots shown before, the cut-point and the efficiencies in both cases were exactly the same.

	T_{Hot} (ºC)	Concentration	Emissivity	Absorptivity	T_{Cold} (ºC)
CSP 1	600	500	0.4	0.9	25
CSP 2	600	1000	0.8	0.9	25



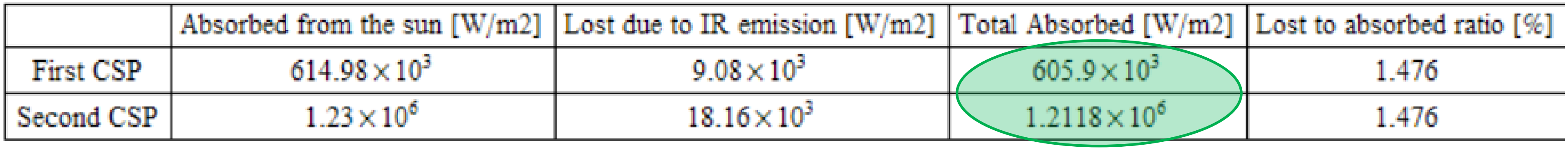
	Absorbed from the sun [W/m2]	Lost due to IR emission [W/m2]	Total Absorbed [W/m2]	Lost to absorbed ratio [%]
First CSP	614.98×10^3	9.08×10^3	605.9×10^3	1.476
Second CSP	1.23×10^6	18.16×10^3	1.2118×10^6	1.476



Not absorbed energy [W/m2]	Not emitted energy [W/m2]	Absorption loses [%]	Emission savings [%]
6.94785×10^3	17.2628×10^3	1.11715	65.5311
13.8957×10^3	34.5257×10^3	1.11715	65.5311

Development of Mathematica Model

- If both cases have the same efficiency, investing in doubling the amount of heliostats does not seem logical as it is much more expensive than using a material with half the emissivity. However, as proven by this model the amount of absorbed energy is way bigger in the case where the concentration is bigger, despite of having a worse emissivity. Therefore, the investment could have been justified.



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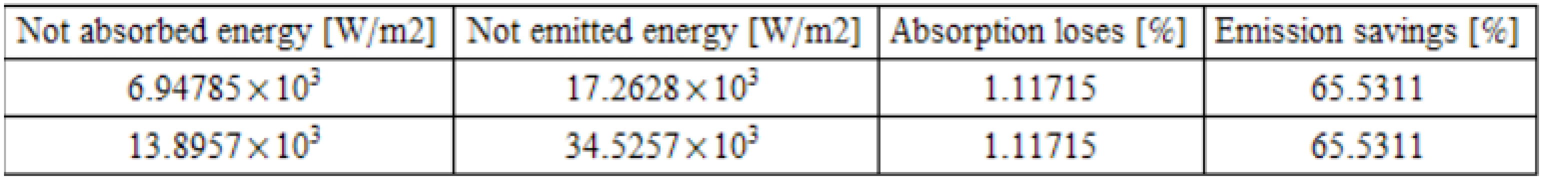

Not absorbed energy [W/m2]	Not emitted energy [W/m2]	Absorption loses [%]	Emission savings [%]
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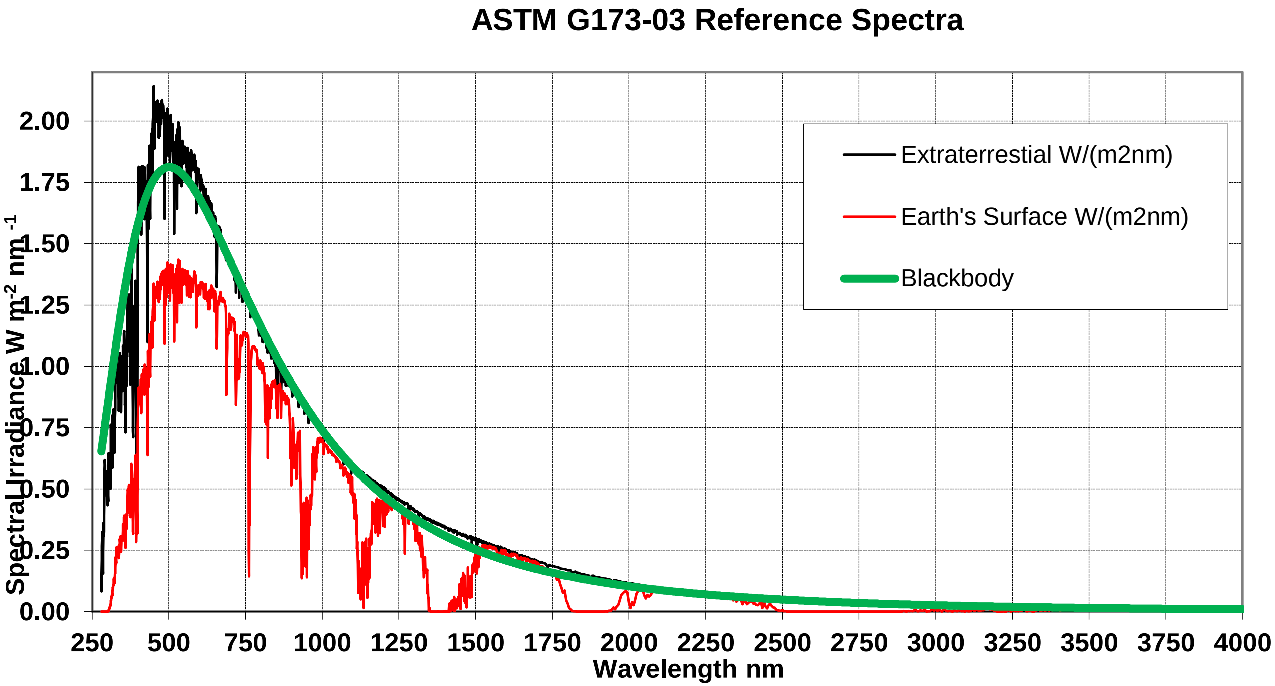
13.8957×10^3	34.5257×10^3	1.11715	65.5311

Development of Mathematica Model

- However, even if sun’s radiation has been assumed to be a blackbody radiation for simplicity’s sake, it’s actually not
- American Society for Testing and Materials (ASTM) and government research and development laboratories developed and defined a standard terrestrial solar spectral irradiance distribution
- "AM1.5", 1.5 atmosphere thickness, corresponds to a solar zenith angle of z=48.2°
- AM1.5 is useful to represent the overall yearly average for mid-latitudes
- The specific value of 1.5 was selected in the 1970s for standardization purposes, based on an analysis of solar irradiance data in the United States

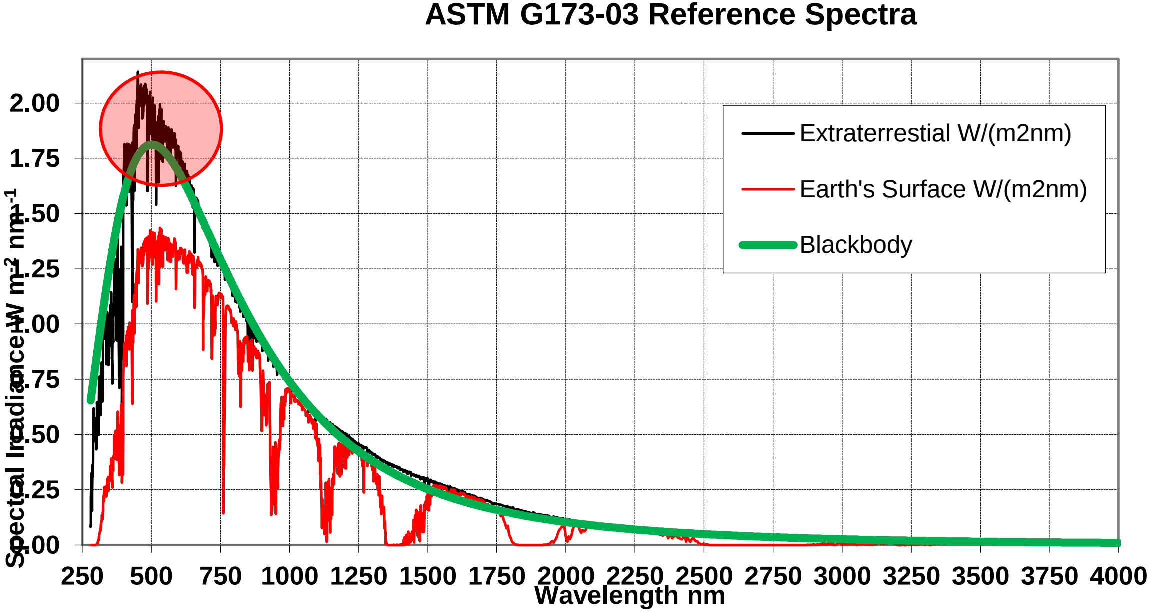
Development of Mathematica Model

- The black line shows the extraterrestrial sun’s radiation. The green line shows the blackbody radiation of a body at sun’s surface temperature. The red line is the actual solar radiation at Earth’s surface



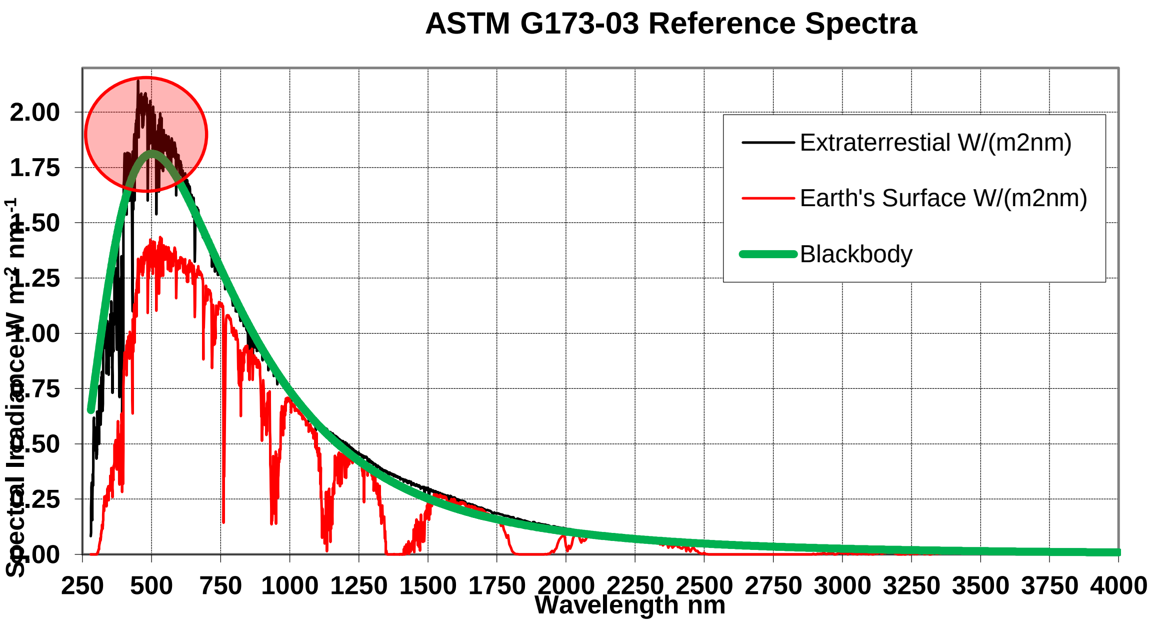
Development of Mathematica Model

- The main reason why this spectrum does not fit Planck’s distribution is because in the mentioned distribution a single surface temperature is assumed. The sun is not a solid with a clearly defined outer face, but a ball of gas and plasma composed of several layers at different temperatures.



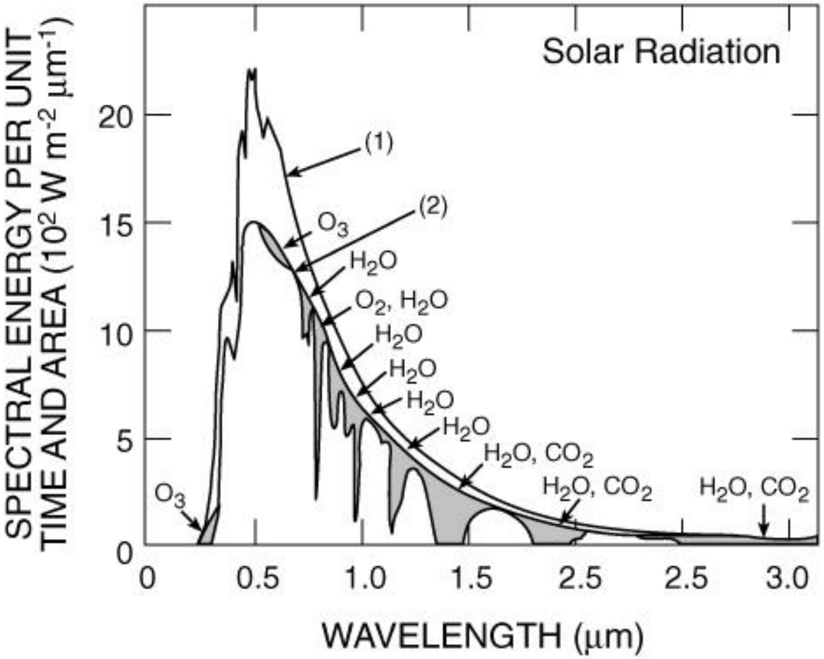
Development of Mathematica Model

- In addition, the effective temperature of 5778 K is based on total radiative power, the area under the curve of the Planck distribution. If the spectrum of sunlight falls short of the 5778 K black body spectrum some wavelengths it must necessarily rise above the 5778 K black body spectrum at others



Development of Mathematica Model

- The discrepancies between the extraterrestrial radiation and the radiation that actually hits the Earth are explained with the absorption bands the elements in the atmosphere have



Source: www.paos.colorado.edu

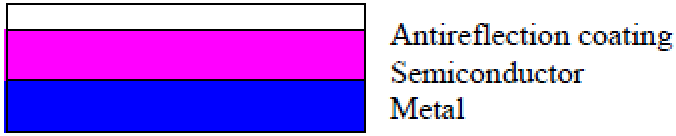
Types of proposed solutions for CSP IR loss avoidance

- Multiple material structures have been proposed that meet the desired properties:
  - Semiconductor-metal tandems
  - Multilayer absorbers
  - Metal-dielectric composite coatings (Pyromark + nanofoam)
  - Textured surfaces

*C.E. Kennedy, Review of Mid- to High- Temperature Solar Selective Absorber Materials, NREL, July 2002

Semiconductor-metal tandems

- Semiconductors with bandgaps from 0.5eV to 1.26eV that absorb short-wavelength radiation are used, and the underlaying metallic layer provides low emittance
- Antireflection coatings are needed because the useful semiconductors have high refractive indices
- The used semiconductors include Si(1.1eV), Ge(0.7eV), PbS(0.4eV)



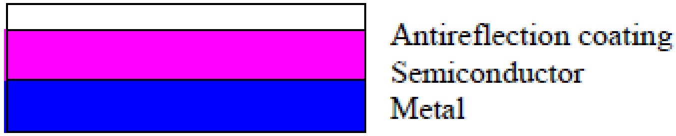
Source*

*C.E. Kennedy, Review of Mid- to High- Temperature Solar Selective Absorber Materials, NREL, July 2002

Semiconductor-metal tandems

- The development of this type of materials were mainly developed in the 70's*

- Even if good results were reported (absorptivity of 0.89 and emissivity of 0.05 at 500ºC)*, no recent research has been found in the field



Source*

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*C.E. Kennedy, Review of Mid- to High- Temperature Solar Selective Absorber Materials, NREL, July 2002

Multilayer absorbers

- This type of absorber is formed by several layers of metallic and dielectric materials
- Overall, they all have the same structure:
  - D has high reflectance in the IR region and is slightly less reflective in the visible region
  - C reduces the visible reflectance
  - B further reduces the reflectance in the visible region
  - A increases the absorption in the visible region and broadens the high absorption region

Source*

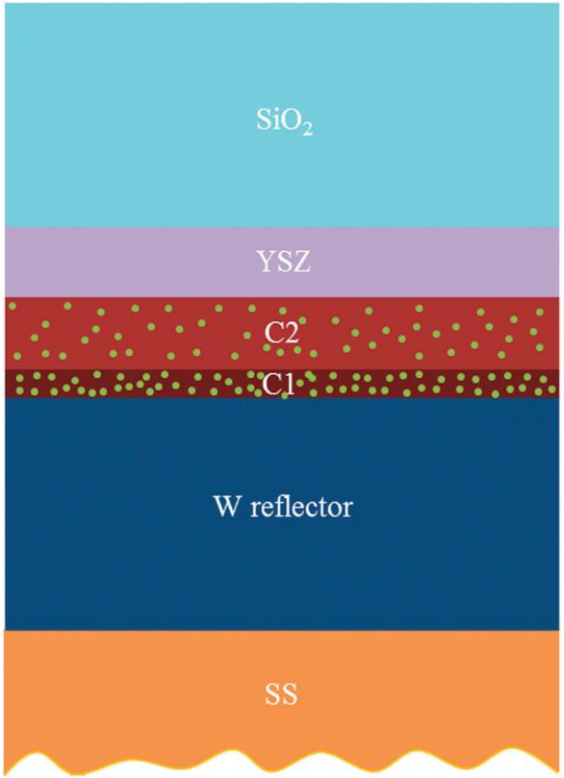
*C.E. Kennedy, Review of Mid- to High- Temperature Solar Selective Absorber Materials, NREL, July 2002

Multilayer absorbers

- The multilayer with the best results found to date is the developed in the next paper:

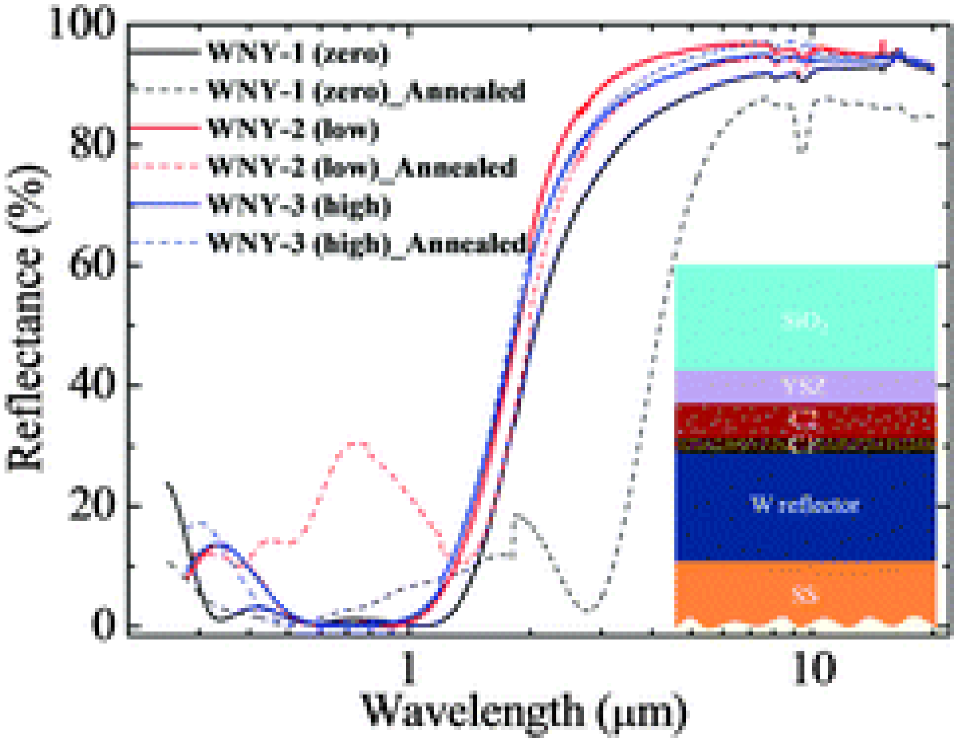
A high-performance spectrally-selective solar absorber based on a yttria-stabilized zirconia cermet with high-temperature stability, Feng Cao, Daniel Kraemer et al., The Royal Society of Chemistry, Energy Environ. Sci., 2015, 8, pp. 3040-3048 materials

- They developed a material with a solar absorptance of 0.91 and a total hemispherical emittance of 0.13 at 500ºC



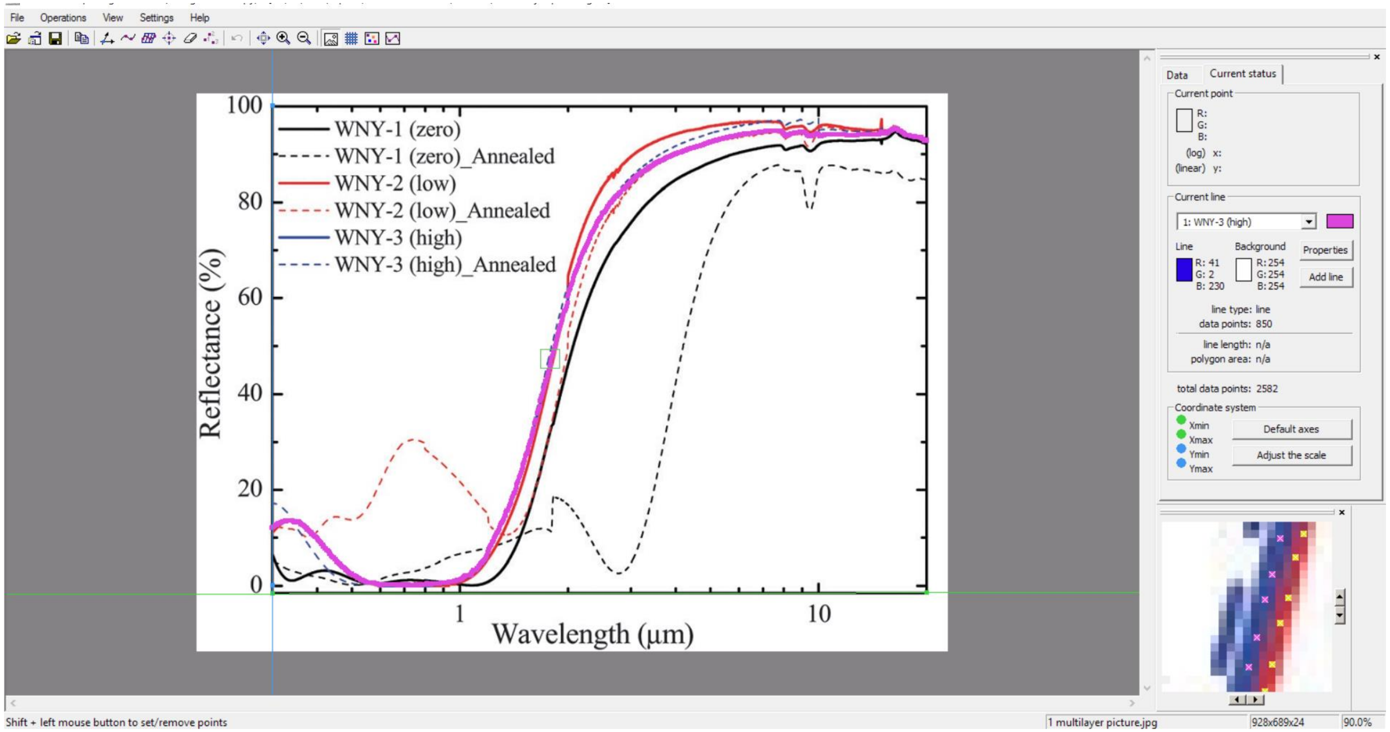
Multilayer absorbers

- The paper shows a reflectance vs wavelength graph
- The first step was to obtain the numerical data from the graph



Multilayer absorbers

- In order to do so, *Graph Data* has been used
- Fixing the axis and plotting dots on top of the curve it calculates the dot’s x and y coordinates and exports them to an excel sheet



Current point
R:
G:
B:
(log) x:
(linear) y:

Current line
1: WNY-3 (high)

Line: R: 41, G: 2, B: 230
Background: R: 254, G: 254, B: 254

line type: line
data points: 850
line length: n/a
polygon area: n/a

total data points: 2582

Coordinate system
● Xmin
● Xmax
● Ymin
● Ymax

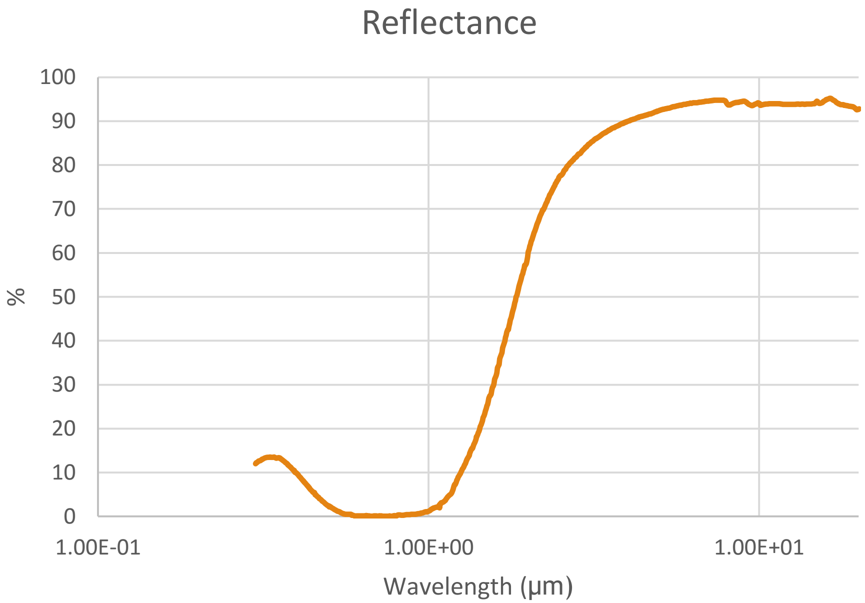
Shift + left mouse button to set/remove points

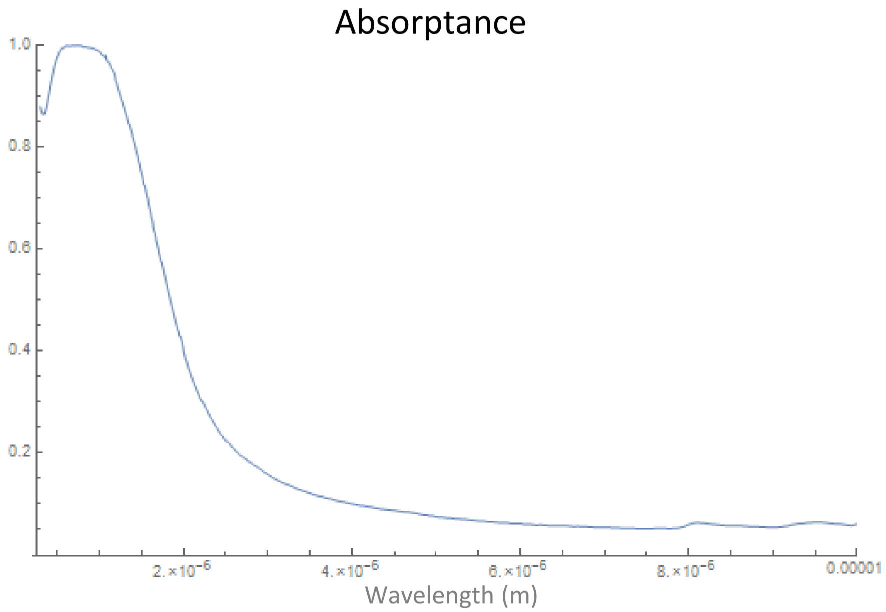
1 multilayer picture.jpg | 928x689x24 | 90.0%

Multilayer absorbers

- From the excel sheet, the absorptance curve was obtained using:

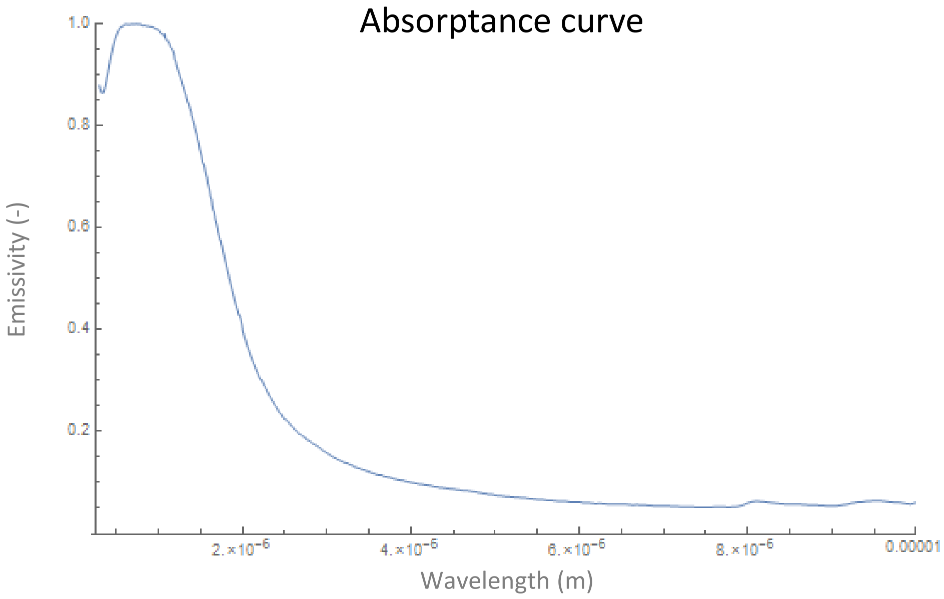
Reflectance = 1- Absorptance


Reflectance


Absorptance

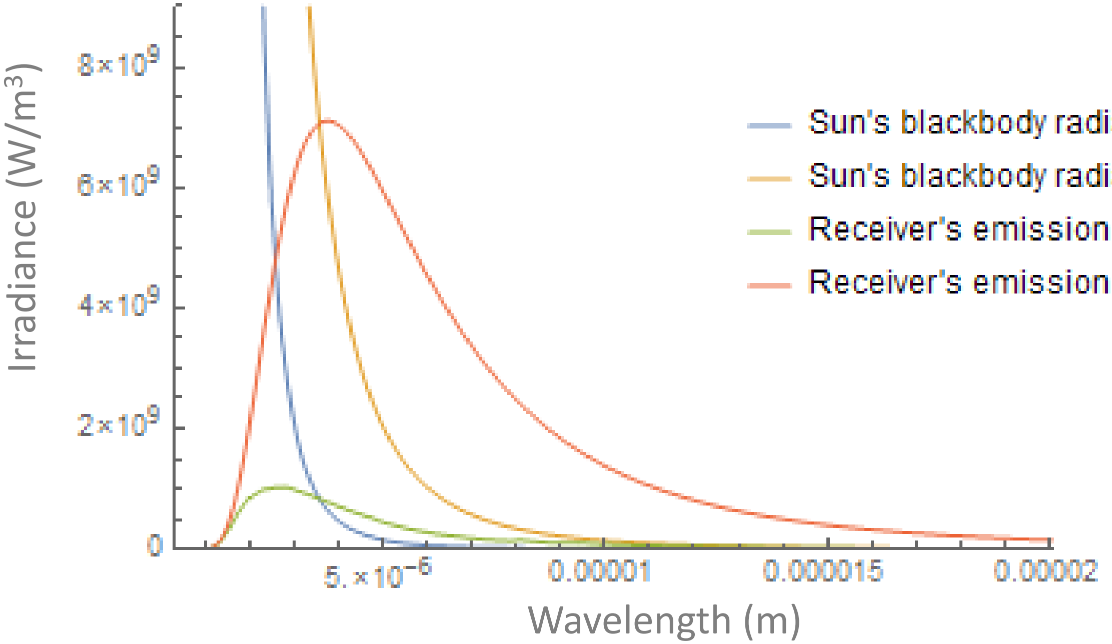
Multilayer absorbers

- Obtained curve is a discrete line (set of 800 points), and as it is not possible to multiply a function by a set of points, this set of point has been interpolated to a function with Wolfram Mathematica



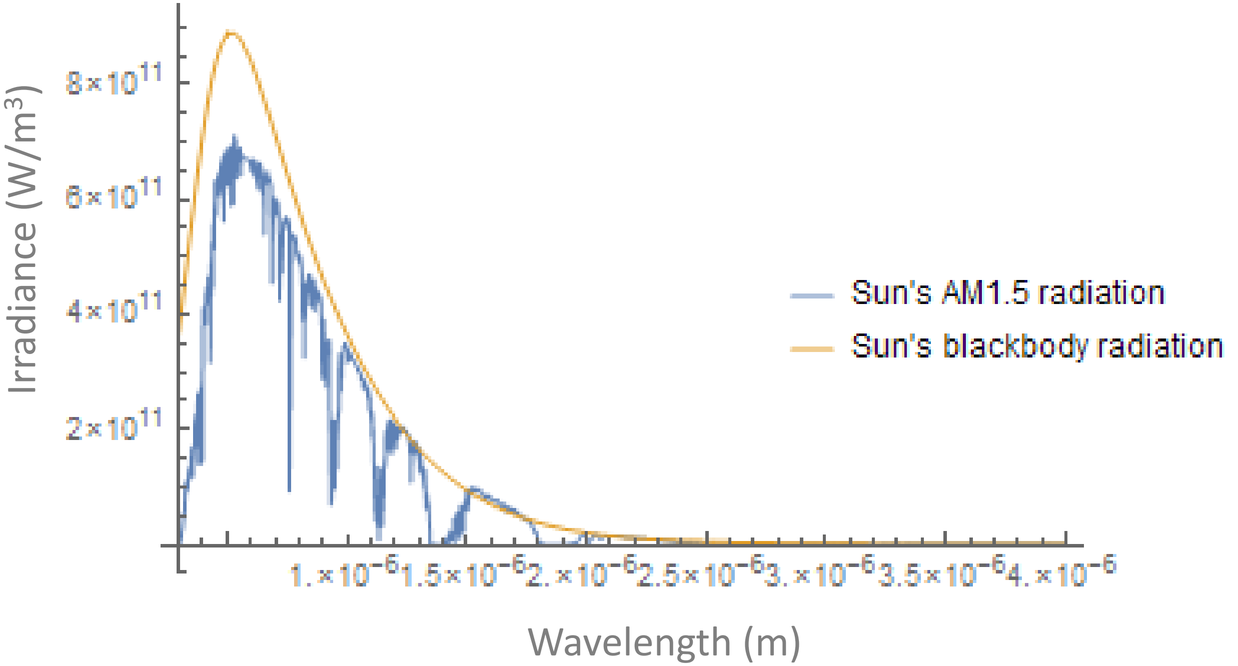
Multilayer absorbers

- Multiplying the interpolated emissivity by the sun’s blackbody radiation and by the receiver’s blackbody emission at 500ºC (A concentration of 500 has been assumed)



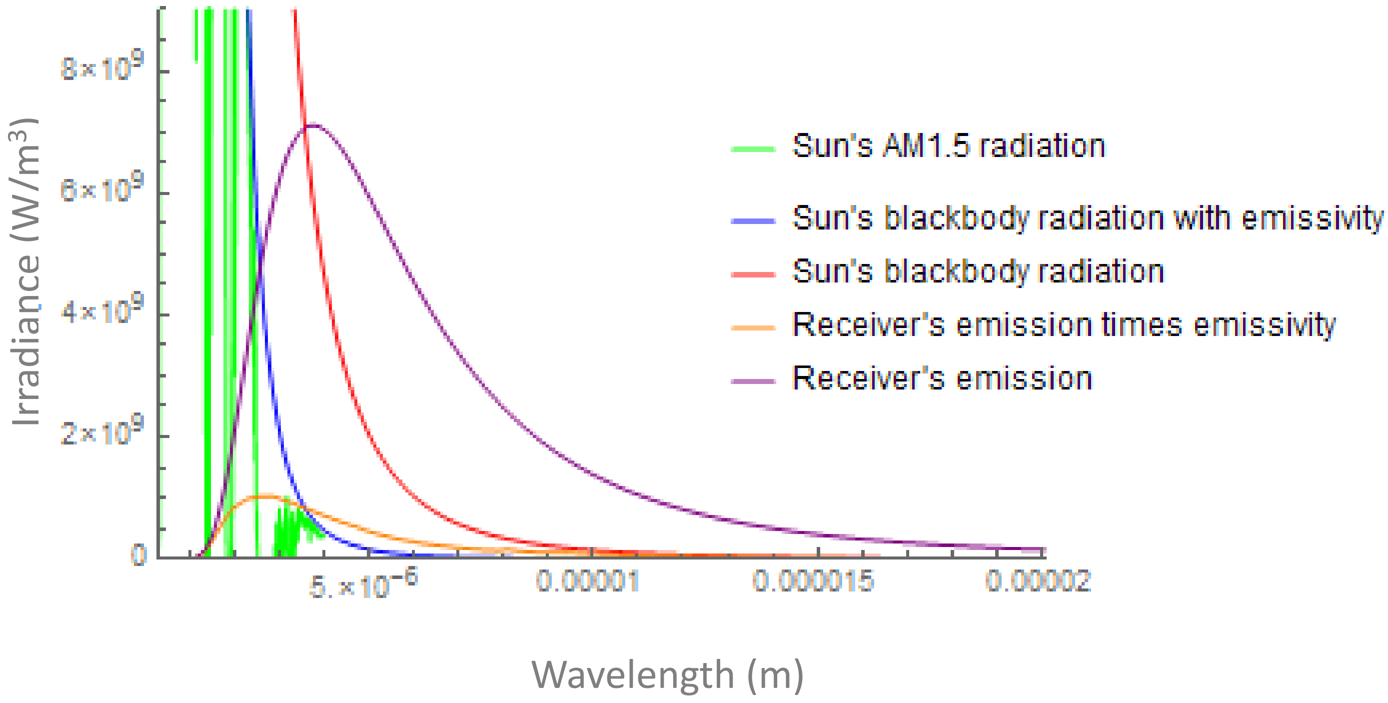
Multilayer absorbers

- Nevertheless, we mentioned that the true solar spectrum is not the blackbody radiation, so the data from the AM 1.5 spectrum has been imported to the program and the dots have been interpolated to obtain a function that would contain them all



Multilayer absorbers

- Plotting all the curves together (Sun’s AM1.5 radiation has been multiplied by emissivity too),



Multilayer absorbers

- The areas of the graph have been calculated and the following numbers have been obtained:

C=500	With Multilayer (W/m2)	Without Multilayer (W/m2)
Emitted	4,036.8	39,328.6
Absorbed	414,388	450,071
Total absorbed	410,351	410,743

- It is assumed that without the SSC the body acts as a blackbody
- Absorption improves 0.095 % without the Multilayer

Multilayer absorbers

- Concentration plays an important role, as can be seen in the table below and comparing it to the previous example:

C=100	**With Multilayer (W/m2)**	**Without Multilayer (W/m2)**
Emitted	4,036.8	39,328.6
Absorbed	82,877.6	90,014.2
Total absorbed	78,840.8	50,685.6

- It is assumed that without the SSC the body acts as a blackbody
- Absorption improves 55.549 % with the Multilayer

Metal-dielectric composite coatings

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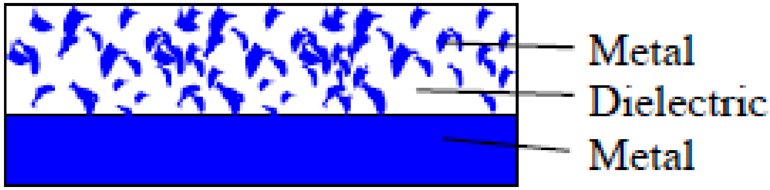
- This type of materials use a single or various layers of what are called *cermets* (a composite material formed of a ceramic matrix and metal particles)
- They usually are highly absorbing coatings in the solar region that are transparent in the IR, deposited onto a highly IR-reflective metal substrate*
- The currently widely used Pyromark® 2500 series are paintings that fall into this type of coating



Source*

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*C.E. Kennedy, Review of Mid- to High- Temperature Solar Selective Absorber Materials, NREL, July 2002

Metal-dielectric composite coatings

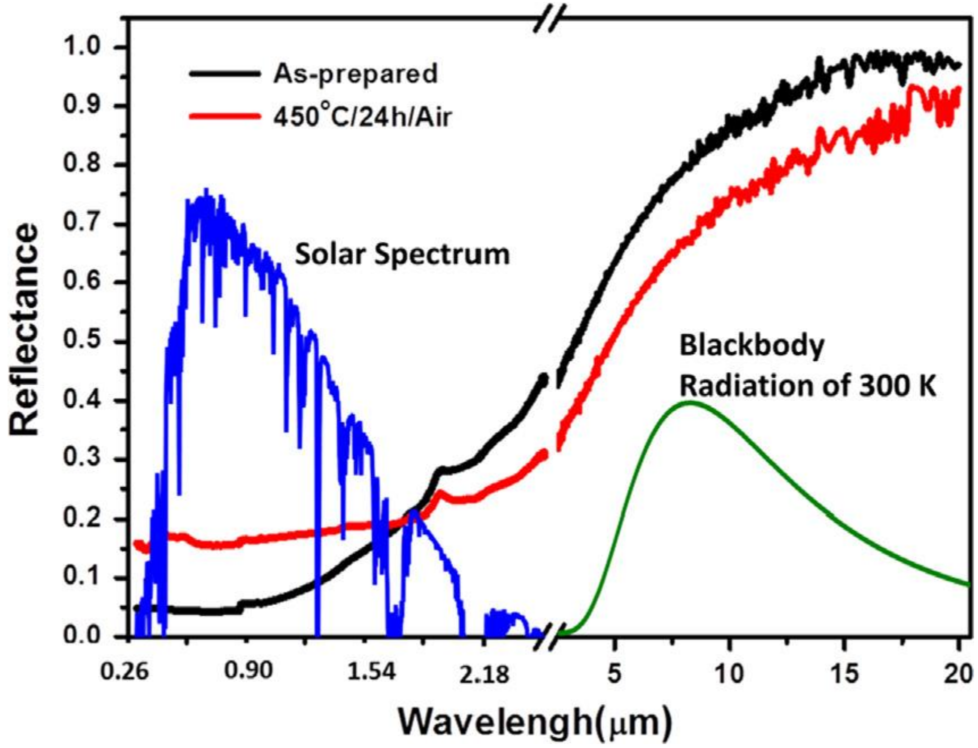
- The best results found are in the following paper:

Xingli Wang, Xiaofend Wu, Long Yuan, Cuiping Zhou, Yanxiang Wang, Keke Huang, Shouhua Feng, *Solar selective absorbers with foamed nanostructure prepared by hydrothermal method on stainless steel*, Solar Energy Materials & Solar Cells 146 (2016), pp. 99–106

- They achieved a solar absorptance of 0.92 and a thermal emittance of 0.12

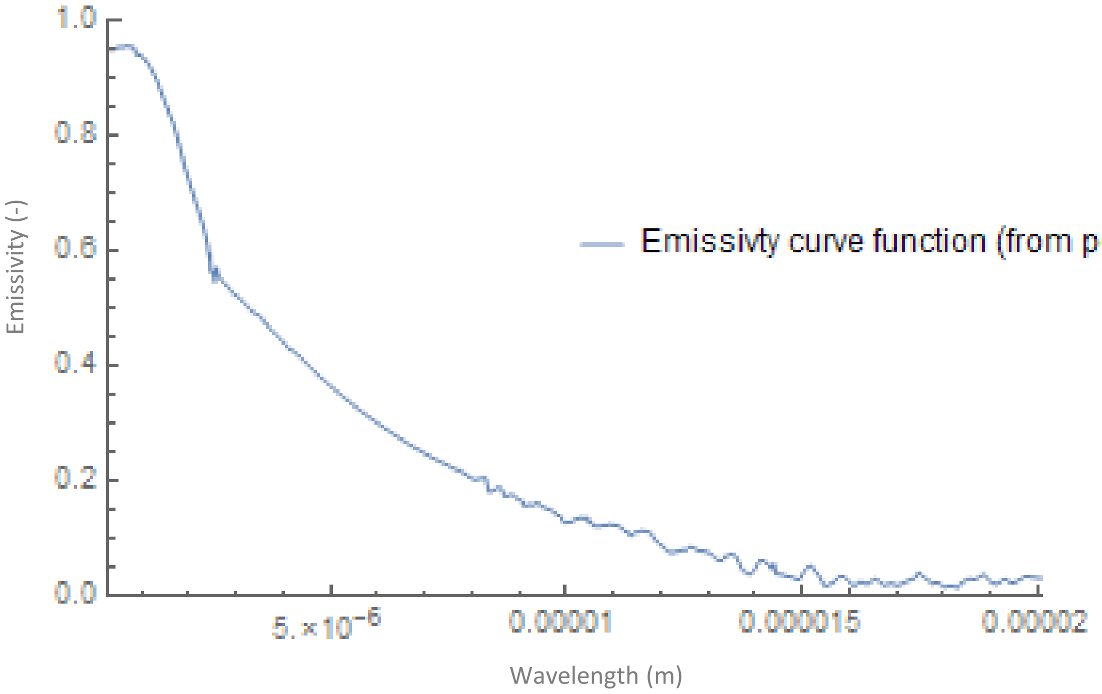
Metal-dielectric composite coatings

- However, they measured it at 300K
- This is the graph they show on the paper



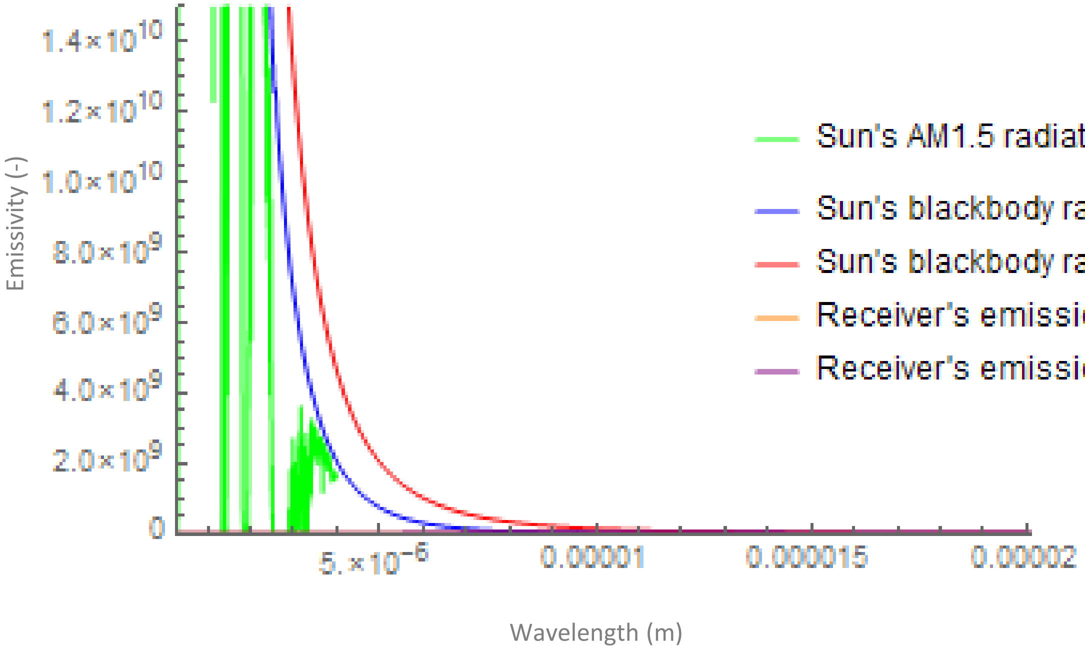
Metal-dielectric composite coatings

- Following the same process as with the multilayer absorbers, a function was created with the dots imported with the *Graph Data*



Metal-dielectric composite coatings

- The tested temperatures are so low that they do not even appear on the graph at this scale (Concentration of 500)



Metal-dielectric composite coatings

- The areas of the graph have been calculated and the following numbers have been obtained:

C=500	With Coating (W/m2)	Without Coating (W/m2)
Emitted	85.5	677.7
Absorbed	415,954	450,071
Total absorbed	415,869	449,394

- It is assumed that without the SSC the body acts as a blackbody
- Absorption improves 8.06 % without the Coating
- However there is no point on using this numbers as the materials has been tested at 300K

Metal-dielectric composite coatings

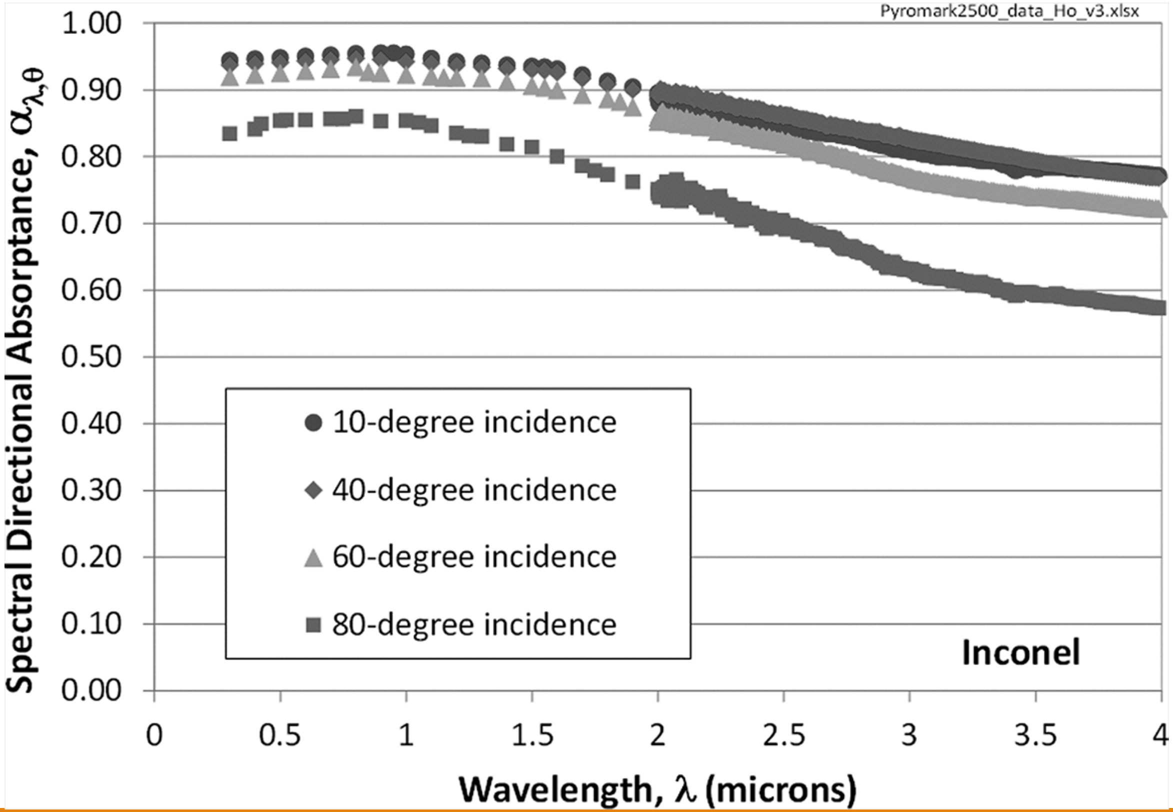
- The same procedure was followed to know what happens with the currently being used Pyromark® material. To do so, the following paper was studied:

Ho CK, Mahoney A, Ambrosini A, Bencomo M, Hall A, Lambert TN. Characterization of Pyromark 2500 Paint for High-Temperature Solar Receivers. ASME. *J. Sol. Energy Eng.* 2013;136(1):014502-014502-4. doi:10.1115/1.4024031.

- Pyromark® has an absorptance of up to 97% and an emittance of around 88% at 700ºC

Metal-dielectric composite coatings

- The study shows the following graph, from which data has been obtained



Metal-dielectric composite coatings

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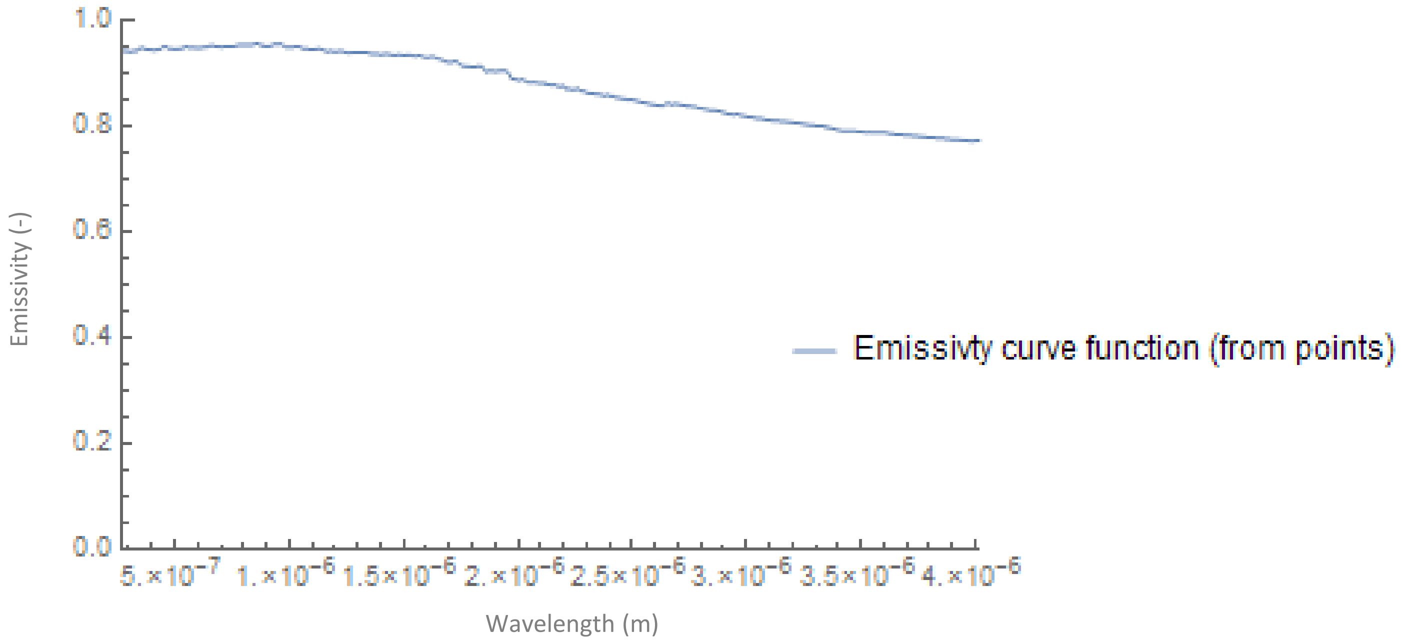
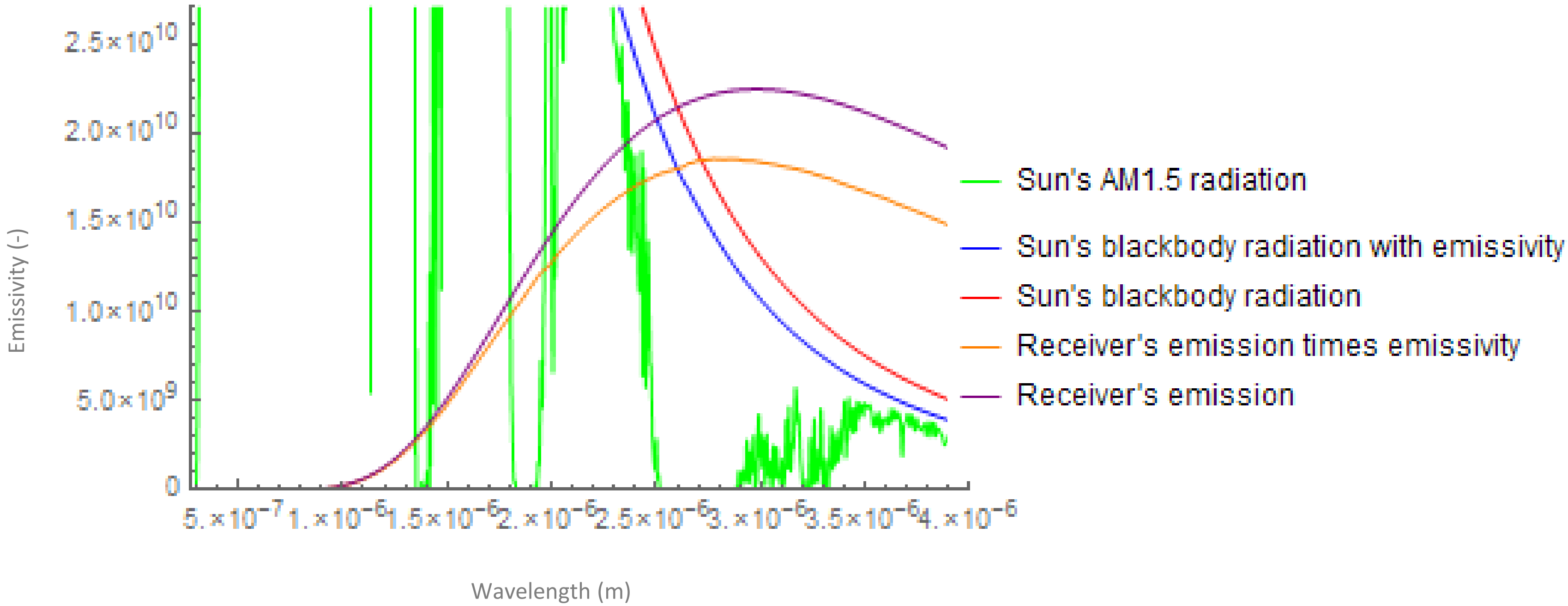
- The study does not show the whole wavelength spectrum, it only measures emissivity until 4 microns, which will limit the ability to compare it with the rest of the materials



Metal-dielectric composite coatings

- This is the full graph up to 4 microns



Metal-dielectric composite coatings

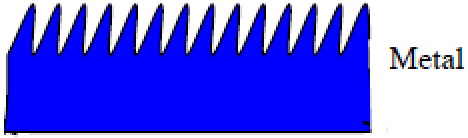
- The areas of the graph have been calculated and the following numbers have been obtained:

C=500	With Coating (W/m2)	Without Coating (W/m2)
Emitted	39,031	46,849.8
Absorbed	424,529	450,071
Total absorbed	385,497	403,222

- It is assumed that without the SSC the body acts as a blackbody
- Absorption improves 4.6 % without the Coating
- However there is no point on using this numbers more than as an orientation way as the test has only ben performed up to 4 microns

Textured surfaces

- The aim of texturing the surface of a metal is to obtain spectral selectivity by the optical trapping of solar energy. The idea is to absorb solar energy while appearing highly reflective to thermal energy
- This technology is not very sensitive to severe environmental effects (oxidation, thermal shock…) that usually are catastrophic to the multilayer structures, but they are strongly affected by abrasion
- There are several fabrication techniques: Unidirectional solidification of eutectic alloys, lithography with X-rays, ion-exchange reactions between metals, vapor-liquid-solid mechanism, vapor deposition, oxidation of metals at high temperatures…



Source*

*C.E. Kennedy, Review of Mid- to High- Temperature Solar Selective Absorber Materials, NREL, July 2002

Textured surfaces

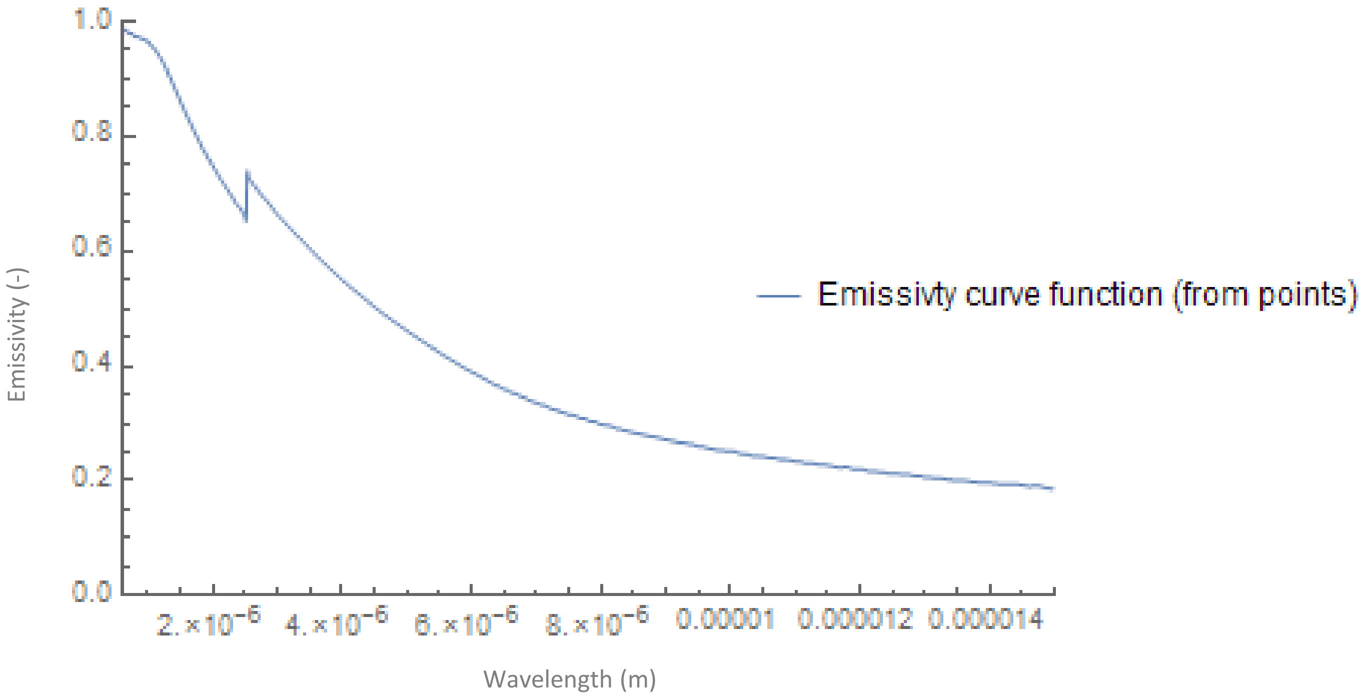
- Despite it was published in the 80's, the following paper shows some of the best results to the best of my knowledge:

G.L. Harding, M.R. Lake, *Sputter etched metal solar selective absorbing surfaces for high temperature thermal collectors*, Solar Energy Materials 5 (1981) pp. 445-464

- They achieved an absorptivity of 0.93 and an emissivity of 0.24 at 400ºC

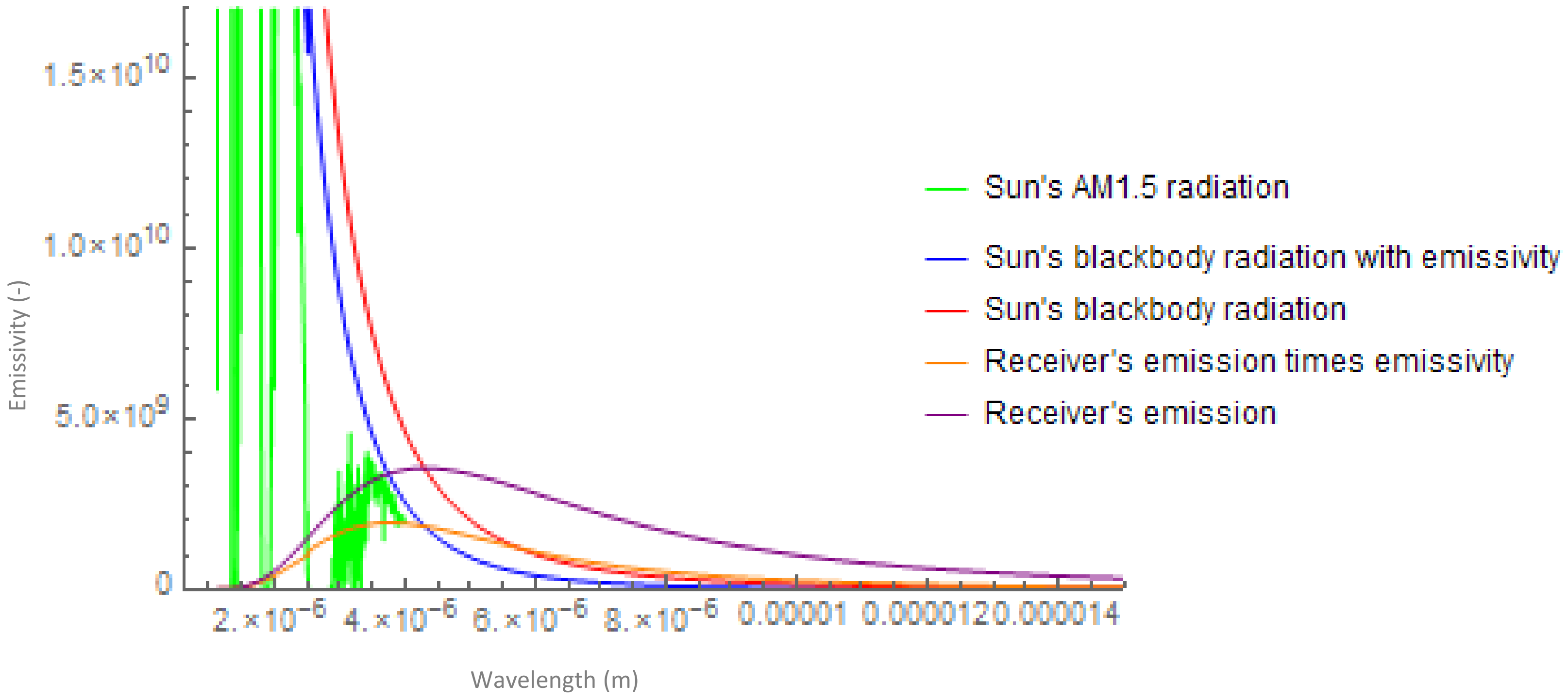
Textured surfaces

- Even if it is not recent, the following paper shows some of the best



Textured surfaces

- Even if it is not recet, the following paper shows some of the best



Textured surfaces

- The areas of the graph have been calculated and the following numbers have been obtained at 400ºC:

C=500	With Textured Surface (W/m2)	Without Textured Surface (W/m2)
Emitted	27,655	22,308
Absorbed	284,858	304,860
Total absorbed	257,202	282,552

- It is assumed that without the SSC the body acts as a blackbody
- Absorption improves 9.85 % without the Textured Surface

Conclusion

- The calculation of the values have several sources of errors:
  - The reflectance curves provided by most of the studies show bidirectional reflectance, which can underestimate actual hemispherical emission in up to 30%
  - Getting set of points from a picture is not an accurate method of obtaining data
  - Solar AM 1.5 spetcrum's data ends at 4 microns
  - Calculated power values omit η_{optic} and $\eta_{electric}$
  - Concentration and temperature have been assumed to be independent factors but further research must be done to find if there is any correlation

Conclusion

- Unless more information is found about the relationship between temperature and concentration, the Surface Selective Coatings (SSC) seem not to be that effective at high concentrations. The problem of the currently found SSCs is that the cost of lowering emissivity is reducing absorptivity. At high concentrations this is crucial because losing a 3% of solar absorptance, in absolute values can be more than what is saved reducing 90% of the emittance (specially at lower temperatures)
- Therefore, use of SSCs is justified at very high working temperatures and not that high concentrations (as long as they keep reducing absorptivity in order to lower emissivity)

Conclusion

- For temperatures below 1000ºC, reducing emissivty can be as important as lowering the cold focus' temperature (specially if reducing emissivity implies reducing absorptivity)
- It is hard to compare different techniques and decide which one is best, as every research group has its own testing criteria and the spectra or temperature at which they test their materials is not the same
- Moreover, many research groups heat their materials to up to 600ºC, but they test the emissivity back at room temperature which makes results incomparable

Conclusion

- For a coating to properly work at high temperatures it needs to undergo without losing its properties several heating and cooling cycles, and must be stable in air at the working temperatures. To the best of my knowledge, the materials that have been tested at higher temperatures were only stable in vacuum, and if they were stable in air either they lost their properties or were only tested for no more than 72 hours

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Metamaterials for Concentrated Solar Power applications

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04/15/2016

Thank You