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Predicting the Impact of Different Cooling Systems on the Performance of Parabolic Trough Concentrating Solar Plant based on Real Data

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ABSTRACT

By enhancing the availability and dispatchability of energy, concentrated solar power systems with thermal energy storage have a significant impact on tackling the issue of energy insecurity in hot and arid locations. However, these technologies currently face a number of difficulties. Additionally, the selection of the cooling system has a significant impact on how well a concentrated solar power plant performs. The primary three drawbacks of current cooling systems are their high-water usage, high cost, limited availability of local water resources, and potential for localized disturbance.

As a result, effective low-water cooling solutions for solar power concentration are highly desired. To achieve this, the study assesses the viability and advantages of adding a radiative cooling system to an indirect parabolic trough-concentrating solar thermal plant with two thermal energy storage tanks in arid regions of Algeria. This system is expected to improve the block and efficiency of the power plant and decrease energy costs and water volumes consumed. In order to evaluate these advantages, using the system advisor model software, a number of simulation models have been constructed including wet, dry, and radiative cooling systems with various configurations so that each strategy can be compared. The experimental statistics from the Andasol-1 plant in SPAIN that were documented in the literature were used for plant parameters. The results of the simulations were contrasted with a predetermined set of posted data from the Andasol-1 reference facility. In comparison to dry and wet cooling systems, the results show a rise in annual power generation and nearly 2.4 % and 11 % increase in the use of radiative cooling systems, respectively. Furthermore, the environmental assessment found that the annual water use may be reduced by 771209.7 m^3, which would result in a possible annual water savings of more than 50%.

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التنبؤ بتأثير أنظمة التبريد المختلفة على أداء محطة الطاقة الشمسية المركزة بتقنية الحوض المكافئ بناءً على بيانات حقيقية

سفيان ميهوب، عبدالإله بن احمد.

ملخص: لمحطات الطاقة الشمسية المركزة مع نظام تخزين الطاقة الحرارية تأثير كبير على معالجة مشكلة انعدام أمن الطاقة في المواقع الساخنة والقاحلة. ومع ذلك، فإن اختيار نظام التبريد له تأثير كبير على مدى جودة أداءها حيث تتمثل العوائق الثلاثة الأساسية لأنظمة التبريد الحالية في استخدامها العالي للمياه، وارتفاع تكلفتها، ومحدودية توافر موارد المياه المحلية، وإمكانية حدوث اضطراب موضعي. ونتيجة لذلك، فإن حلول التبريد الفعالة بالمياه المنخفضة لتركيز الطاقة الشمسية مطلوبة بشدة. ولتحقيق ذلك، تقوم الدراسة بتقييم جدوى ومزايا إضافة نظام تبريد إشعاعي إلى محطة حرارية شمسية مركزة على شكل قطع مكافئ غير مباشر مع خزانين لتخزين الطاقة الحرارية في المناطق القاحلة في الجزائر. ومن المتوقع أن يؤدي هذا النظام إلى تحسين كتلة وكفاءة محطة توليد الكهرباء وتقليل تكاليف الطاقة وكميات المياه المستهلكة. ومن أجل تقييم هذه المزايا، باستخدام برنامج system advisor model ، تم إنشاء عدد من نماذج المحاكاة بما في ذلك أنظمة التبريد الرطبة والجافة والإشعاعية بتكوينات مختلفة بحيث يمكن مقارنة كل استراتيجية. تم استخدام الإحصائيات التجريبية من مصنع Andasol-1 في إسبانيا والتي تم توثيقها في الأدبيات لمؤشرات المحطة. تمت مقارنة نتائج عمليات المحاكاة مع مجموعة محددة مسبقًا من البيانات المنشورة من المنشأة المرجعية Andasol-1 . وبالمقارنة بأنظمة التبريد الجافة والرطبة، أظهرت النتائج ارتفاعاً في توليد الطاقة السنوي وزيادة بنسبة2.4% و 11% تقريباً باستخدام نظام التبريد الإشعاعي، على التوالي. علاوة على ذلك، وجد التقييم البيئي أن الاستخدام السنوي للمياه قد ينخفض بمقدار 771209.7 م^3، مما سيؤدي إلى توفير المياه السنوي المحتمل بأكثر من50% .

الكلمات المفتاحية – بالتحسين، نظام التبريد الإشعاعي، محطة الحوض المكافئ، الأداء، محطة أنداسول-1.

1. INTRODUCTION

Advances in alternative energy resources have paved the way for technological advances aimed at improving the energy mix, maximizing their consumption, and converting them into viable solutions [1]. Therefore, Concentrated Solar Power (CSP) facilities are becoming more and more well-liked on a global scale due to their capacity to efficiently utilize and save solar thermal electricity, increasing the dispatchability of this renewable electricity supply and preventing the usage of fossil fuels to generate electricity[2]. CSP facilities are situated in arid areas known as sun belts, which are characterized by high direct normal irradiation (DNI), year-round low water availability, and possibly higher air temperatures. Even better than 40 °C is possible. Moreover, in such extreme settings, cooling solutions like wet and dry cooling are not the best options [3]. Additionally, the temperature of the wet bulb and the amount of moisture in the surrounding air affect the overall thermal performance of wet-cooled plants. The ambient air dry-bulb temperature is one of many factors that affect how well dry-cooled plants operate overall. Therefore, a dry-cooled condenser's total performance is significantly impacted by the seasonal variance in dry-bulb temperature [4]. Moreover, several parameters should be considered to produce sufficient net energy with higher efficiency and lower cost. Among these parameters, the performance of the cooling system, associated with sufficient water availability. Using air at ambient atmospheric temperatures, the steam popping out of the steam turbine cannot attain very low pressure, which influences the net power output, and therefore decreases plant efficiency. At this time, it is difficult to find the optimal option among the many accessible technologies [5], and good sized efforts are being made to discover an approach to those problems. As a result, the radiative cooling system is the brand new answer that could permit discount of water requirement and enhance the power plant performance.

In the literature, all studies have focused on the optimization and enhancement of the overall performance of wet/dry and hybrid cooling mechanisms [6-11], and only a few studies have examined the effect of those cooling mechanisms on the overall performance of CSP plants may be found.

To determine the impact of the cooling systems on the overall performance of the CSP facilities, we used Turchi's [12] research, which used the System Advisor Model software to compare the performance of wet-condensers, mechanical dry air-condensers, and hybrid structures in a parabolic trough solar power plant. With air-cooled technology, it is anticipated that the plant cost and LCOE will decrease by 10 % and 7 %, respectively. The energy, exergy, and exergo-economical evaluation of a 50 MW CSP plant with a wet and dry-cooled condenser were similarly provided by Habl et al.[13]. Due to three additional occurrences of parasitic load in a dry-cooled condenser, they anticipated that the power output with dry cooling is 2.54 MW less than that with wet cooling, and the exergy performance for a plant with wet and dry cooling was 79.8 % and 74.5 %, respectively. Blanco et al [14] examined exergetic dry and wet cooling techniques for the Rankine cycle of a 50 MWe solar thermal power plant. They concluded that operating at low go-out turbine pressures with an air-cooled condenser was not environmentally friendly. At higher pressures, it does, however, become more aggressive. Comparing wet, dry, and hybrid cooling systems for heat dissipation in a solar power plant, Cutillas et al. [15] conducted an Energy, Exergy, and Environmental (3E) analysis based on the pre-cooling of the air in an adiabatic panel positioned in the entry section of a dry system. They discovered that the wet cooling system uses three times as much water as the hybrid cooling system and that for the wet, hybrid, and dry cooling systems, respectively, the plant's energetic performance is 73.77 %, 69.21 %, and 68.46 %. Carolina et al. [16] suggested reducing the water intake of a focused solar tower power plant by using a dry Heller cooling system. They predicted an increase in power production of close to 6% when compared to an autonomously draft dry cooling system and a reduction in power production of significantly less than 3.7 % when compared to a wet cooling system. Another observation made within the same context was made by Faisal et al.[2], who used Thermoflex software to analyze the thermodynamic performance and water intake for various hybrid cooling system configurations for CSP plants. They found that the configuration that saves the most water is series-parallel. Another way to put it is that Aseri et al. [17] represented a review of the available literature and a comparative analysis of the wet, dry, and hybrid condenser cooling technology for CSP plants. They noted that the use of dry or hybrid systems in place of wet cooling could potentially lead to lower thermal performance and increased parasitic energy requirements, resulting in an elevated cost of energy production. However, the equal extra effects result in a 92% reduction in the amount of cooling water needed, which will greatly expand the capacity of solar thermal power plants as sites in arid regions can also be used. A techno-economical evaluation of a steam turbine cycle with wet- and dry-cooling structures was presented by Henry and Diemuodeke in 2021[18] for five typical tropical locations in Nigeria with varying climatic conditions and water usage costs. The results of this observation indicate that the wet cooling system is a good choice for both wet and dry environments, and that plants using wet cooling produced more net energy with lower life-cycle costs and operating and maintenance costs than plants using dry cooling. The overall performance and financial implications of plants with dry cooling have been more advantageous for tropical rainforests and coastal regions with low ambient temperatures and high relative humidity values due to reduced system sizes and expense requirements. An integrated modeling device for a thorough simulation of a CSP plant, including water and wastewater streams, treatment facilities, and treatment costs, was provided by Shahab et al. in 2021[19]. The models were contrasted with a constant measurement of water intake from a commercial CSP plant. The results indicate that with optimum methods, the use of raw water may be reduced by 14% while the cost of energy remains the same or slightly decreases.

Based on previous studies, the cooling water consumption of CSP greatly reduces the benefits of this technology. Therefore, significant efforts are being made to discover an approach to these problems. For this, the radiative cooling system offers a promising solution that could permit a discount on water requirements and enhance the performance of the power plant.

Radiative cooling systems have been considered for several applications such as building cooling, fluid cooling panels, and refrigeration... [20-23] , however, only a few studies that evaluate the potential of CSP power plants with radiative cooling were found. First, Smith PS and Smith OJ [24] developed a radiative cooling unit in the desert using a boiler and several flat-plate solar collectors coated with titanium dioxide to release heat from a Rankine cycle power system's condenser into the chilly sky. This was the first time radiative cooling technology had been used in a CSP thermal plant. After the success of this issue, some studies have been conducted in different ways (water consumption, feasibility, and land area requirements). Using a two-dimensional finite difference heat transfer model of the radiator, Dyreson and Miller [25] examined the viability of a radiation-enhanced cooling system for concentrating solar thermal power plants, where no water is consumed. The findings indicate that when the night-sky cooling system is the same size as the solar field, it can supply more than 90 % of the necessary cooling. Moreover, compared to 4% for conventional air cooling, the water parasitic load in the radiator system is just about 1% of the annual energy output. The night sky cooling technology, in particular, offers hope for resolving the water issue that CSP power plants in sunbelt areas face. The combined solar energy-radiative cooling systems were similarly examined by Salman et al [26]. In step one, taking into account module configurations, system designs, materials employed, operating circumstances, and performance outcomes. After that, the most current developments to address their problems with inadequate cooling, strict spectrum requirements, and changes in energy supply and demand have been explored. Based on historical meteorological datasets from throughout the world, Ablimit et al. (2021)[27] calculated the worldwide radiative cooling potential in terms of net cooling power density and assessed it in terms of cooling degree days and population density. According to the findings, areas that are geographically and demographically situated between rainy and dry climates as well as sparsely and highly populated areas are most suited for the deployment of radiative cooling technology. The same research, utilizing air spectral emissivity, was conducted by Zhu et al. [28] for 271 sites in China. Various radiative cooling surfaces (ideal selective, ideal selective, semi-ideal selective, and ideal wideband) are taken into consideration. The outcomes of this research can serve as recommendations for radiative sky-cooling system design in China.

In another study focused on water consumption, Ablimit et al.[29] used a reference CSP plant, the Mojave Solar Project, under various weather conditions in over 3,000 locations to investigate the possibility of reducing water use in recirculating wet-cooled CSP plants in the southwestern U.S. regions by integrating radiative cooling and cold storage systems. The findings of this study indicate that daytime radiative cooling can cut yearly water usage by 40 % to 60 %, while daytime radiative cooling and cold storage systems together have the potential to reach annual water savings of 65% to 8 5%. The day-night radiative sky-cooling water potential in thermal power plants with and without evaporative wet cooling was examined in another study by the same author, Ablimit et al.[30]. When the radiative cooling system was used as a stand-alone cooling system, they discovered that 100 % water savings could be attained with a substantially lower efficiency penalty and auxiliary power usage than that of stand-alone dry cooling systems

To optimize land use, Zeyghami and Khalili [31] evaluated the needed area of a daytime radiative cooling system for a CSP plant in various instances with two cycles in order to maximize land utilization. Recompression and simple S-CO2 cycles are used to assess the minimal plant radiative cooling fields. According to the study's findings, two S-CO2 cycles working at a heat storage temperature of 800 °C need 4.38 and 10.46 m2/kW of radiative coolers, which correspond to performance gains of 3.1 % and 4,9 %, respectively. In a separate study, Espargillier et al.[32] examined the viability of replacing the wet cooling towers and dry coolers in CSP power plants with a huge linear Fresnel and a parabolic trough of mirrors, respectively. According to their research, the radiative cooling system could provide 95% and 53%, respectively, of the cooling needs of linear Fresnel and parabolic trough solar power plants.

As stated earlier, water scarcity, parasitic loads of fluid circulation, poor cooling capacity, and thermal-efficiency penalties are some of the major difficulties in the development of CSP thermal power plants using active cooling techniques (i.e., air/water cooling) over the years. Therefore, it's critical to boost cooling technology performance to lessen CSP power plants' need on water. Several cooling technolgies have been suggested (wet, air-cooled, hybrid and radiative). The radiative cooling system being the most effective among the others [33]. Furthermore, no research has been done on how this new cooling system (radiative cooling) will affect a Parabolic Trough Concentrating Solar Thermal Power Plant's (PTCSTPP) overall performance, including technical aspects, water needs, overall thermal performance, and economic and environmental impacts. Thus, this paper's goal is to evaluate how these factors affect PTCSTPP and improve the efficiency of the PTCSTPP, TES, and radiative cooling system.

The reference type power plant "Andasol-1" in Spain was utilized for the simulation model's parabolic trough solar power plant by using experimental data from the literature. The research mentioned above also indicates that a radiative cooling system can be utilized to cool CSP plants, although it is not obvious how this technology would function in various climates and how the potential water savings of these places vary. Thus, a case study of various Algerian climatic regions situated within side the Middle East and North Africa (MENA) regions considered to be some of the areas with the very best DNI values worldwide have been added, taking into account the advantage of desert meteorological conditions where CSP plants are located. Finally, a collection of public data from the Spanish "Andasol-1" plant was compared to the outcomes of the simulations.

2. MATERIALS & METHODS

2.1. Parabolic Trough Concentrating Solar Power Plant

Two essential components make up a CSP plant: the power block (PB) and the solar field (SF). A significant portion, thermal energy storage (TES), is optional but will eventually become nearly necessary. Since it may store thermal energy before transformation and use it when solar radiation is insufficient, it is a property that applies to all types of CSP plants in the field of renewable energies. The generation of concentrated solar power using a parabolic trough is the most advanced. It primarily gains from the knowledge gained from the Californian SEGS power plants built in the 1980s and still in use. Thus, the reliability and longevity of this technique are demonstrated.

Using the first principles of heat transfer and thermodynamics to characterize many system components, the parabolic trough model used in the simulation determines the power fed into the grid from a parabolic trough solar array that provides thermal energy to the power block for electricity generation via an optional thermal energy storage system.

The formula below provides the solar field's efficiency [34]:

$$\eta_{sf} = \sum_{i=1}^{N_{SCA}} \eta_{geo} . \eta_{opt} . \eta_{iam} . \eta_{th} . \eta_{field} \qquad (1)$$

The effective energy transfer rate is expressed by [33]:

$$Q_{sf} = Q_{sun} . \eta_{sf} = I_{bn} . A_{ap,tot} . \eta_{opt} \qquad (2)$$

I_{bn} is the direct normal beam;

The heat losses of the pipes in a loop are determined by the following empirical equation [35]:

$$P_{sf,pip} = 0.01693\Delta T - 0.0001683\Delta T^2 + 6.78\times 10^{-7}\Delta T^3 \qquad (3)$$

$$\Delta T = \frac{T_{sf,out} + T_{sf,in}}{2} - T_{amb} \qquad (4)$$

The thermal losses of the pipes in a sun area are low, around 10 W/m^2. Then, the net power gathered through heat transfer fluid (HTF) at the area [W/m^2], is the distinction between the heat absorbed withinside the fluid through the absorber tubes and the sum of the thermal losses from the receivers and the piping to and from the sun area:

$$Q_{collec} = Q_{absorbed} - (Q_{recep} + Q_{pip}) \qquad (\ )$$

The amount of energy stored by TES systems can be expressed by :

$$Q = m.C_p.\Delta T \qquad (6)$$

where: m is the mass of storage material (kg), C_p is the specific heat capacity (J.kg^{-1}.K^{-1}) and ΔT is the temperature change during the process.

2.2. Cooling system of Parabolic Trough Concentrating Solar Power Plants

The best portion of the heat released by combustion can be converted into useful work for the generation of electricity, in accordance with the second law of thermodynamics. In this way, any waste heat that must be discharged into a power reservoir that is at a lower temperature. The condensing temperature and the parasitic power required of the specific device serve as particular prompts for the impact of the cooling device on the overall performance of the solar power plant. In solar thermal power plants, unique cooling systems are used. These include:

2.2.1. Cooling towers

A cooling tower is a specialized heat exchanger that employs the evaporative cooling principle to remove waste heat from the coolant. The two fluids, air and water, which can come into direct contact with one another, are used to chill the environment. There are two cooling tower methods available: dry cooling towers and wet cooling towers.

a/- Wet cooling system:

The mechanical draft (pressured or generated) and the natural draft could be the primary supporting elements of the wet-cooled system. The wet-bulb temperature T_{wb} of the cooling air serves as a means of limiting the cooling tower's capacity [36]:

$$\mu = \frac{(T_{in} - T_{out})}{T_{in} - T_{wb}} \times 100 \qquad (7)$$

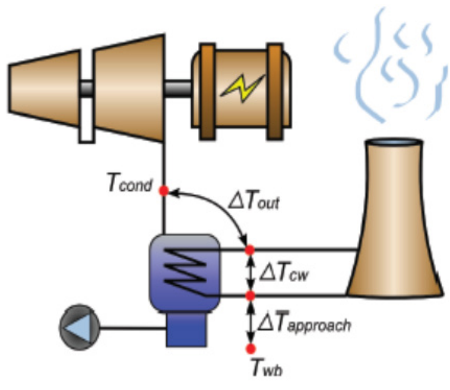

Figure 1. Temperatures that affect condenser pressure for a wet cooling system [37].

The condenser temperature is calculated by the following formula [36]:

$$T_{cond} = T_{wb} + \Delta T_{out} + \Delta T_{cw} + \Delta T_{approach} \qquad (8)$$

b/- Dry cooling system:

Condensers are air-cooled and release their heat into the surrounding area. A fan operates at a speed of 100 m/s to circulate air vapor at a cooling rate of the condenser's ribbed pipes.

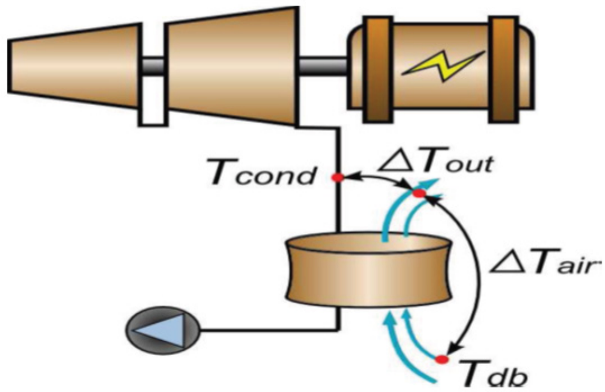

Figure 2. Temperatures that affect condenser pressure for a dry cooling system [37].

The condenser temperature is calculated by the following formula [36]:

$$T_{cond} = T_{db} + T_{ITD} \qquad (9)$$

$$With: \qquad T_{ITD} = \Delta T_{out} + \frac{\dot{q}_{rej}}{\dot{m}_{air} . C_{p,air}}$$

T_{db} is the temperature of the dry air;

$\dot{q}_{rej}$ is the heating load.

2.2.2. Radiative cooling model

The net cooling power (P_{net}) relies upon the sum of radiative emission from the cooler (P_{rad}), the absorption of sun irradiation (P_{sol}) in addition to atmospheric emission (P_{atm}), and the warmth entering through conduction and convection (P_{con}). According to the regulation of power conservation, it is able to be expressed by [22]:

$$P_{net} = P_{rad}(T_s) - P_{sol} - P_{atm}(T_{amb}) - P_{con}(T_{amb}, T_s) \qquad (10)$$

where T_s and T_{amb} are the temperature of the surface and ambient, respectively.

$$P_{rad}(T_s) = \int_0^{2\pi} \int_0^{\pi/2} \int_0^{\infty} \varepsilon_s(\lambda,\theta) I_b(\lambda,T_s) cos(\theta) sin(\theta) d\lambda d\theta d\varphi \qquad (11)$$

$$P_{sol} = cos(\theta_{sol}) \int_0^{\infty} \alpha_s(\lambda,\theta_{sol}) I_{AM1.5}(\lambda) d\lambda \qquad (12)$$

$$P_{atm}(T_{amb}) = \int_0^{2\pi} \int_0^{\pi/2} \int_0^{\infty} \alpha_s(\lambda,\theta) \varepsilon_{atm}(\lambda,\theta) I_b(\lambda,T_{atm}) cos(\theta) sin(\theta) d\lambda d\theta d\varphi \qquad (13)$$

$$P_{con}(T_{amb}, T_s) = h_{con}(T_{amb} - T_s) \qquad (14)$$

Where:

ε_s and α_s are the emissivity and absorptivity of the radiative cooler, $\varepsilon_s = \alpha_s = 1 - \rho_s$ with ρ_s is the reflectivity of the radiative cooler.

εatm is the emissivity of the atmosphere and is represented as $\varepsilon_{atm} = 1 - \tau_{atm}(\lambda)1/\cos\theta$,

where τatm(λ) is the spectral transmissivity of the atmosphere.

Moreover, according to [29], the water temperature drop in the radiative cooling module determines the net cooling power of an individual module:

$$P_{net} = m_w.C_{pw}(T_{rad,in} - T_{rad,out}) \qquad (15)$$

Where:

m_w is the water mass flow rate of a single module:

$$m_w = \frac{m_{cw}}{N} \qquad (16)$$

$$N \text{ is the number of modules}; N = \frac{Cooling\ size}{A_{module}}$$

A_{module} is the module area (m^2).

m_{cw} is the actual cooling water mass flow rate through the power plant condenser (kg/s).

Finally, the radiative cooling system's overall cooling capacity is determined by:

$$P_{net,total} = N.P_{net} = N.m_w.C_{pw}(T_{rad,in} - T_{rad,out}) \qquad (17)$$

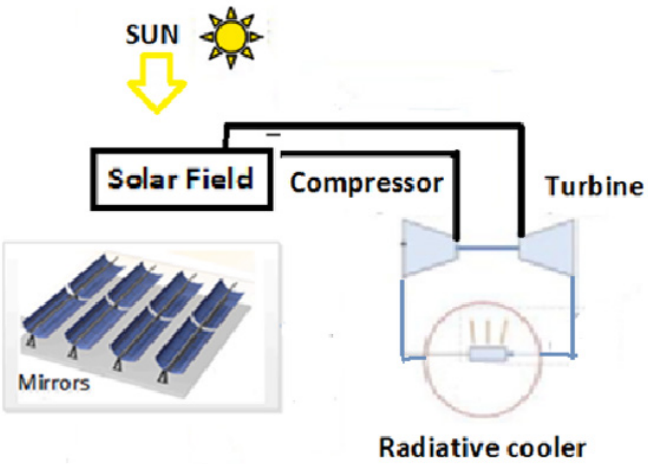

Figure 3. Radiative cooling system in CSP plant.

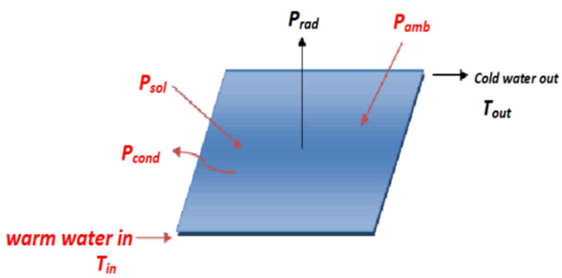

Figure 4. Radiative cooling module.

The simulation's technique is explained as follows:

- Create a simulation base using the same inputs as the reference plant "Andasol-1" in the Tamanrasset site, which is the best and most appropriate location for CSP plants in Algeria, per several studies [38].
- A comparison of the performance of the Tamanrasset power plant's three cooling systems (wet, dry, and radiative) using a techno-econo-environmental simulation of the SAM model.
- Analyzing how the site's attributes, STE full load hours, and plant nominal gross electric power affect the operation of the plant .
- The results' validation against actual data.

3. RESULTS & DISCUSSION

Utilizing the System Advisor Model (SAM) [39-40], a performance improvement of a Parabolic Trough Concentrating Solar Power Plant utilizing the radiative cooling system has been evaluated and confirmed against real data of a reference plant "Andasol-1" in various locations of Algeria. The most pertinent plant technological, economic, and environmental performance measures, such as levelized cost of energy (LCOE), efficiency (CF), total installed cost (TIC), and annual water use (AW), are included in the simulation results.

3.1. Solar plant model

The simulation model's parabolic trough solar power plant is of the Andasol-1 type. The simulation models employed in this work were validated using information from actual CSP facilities, which supports this decision[41]. Experimental data from Andasol-1 that were published in the literature were used for plant parameters.

A parabolic trough solar power plant (CSP) called Andasol-1 is situated in Arder, Spain, around 40 km east of Granada. This is the first integrated heat storage trough power plant in the world as well as the first trough parabolic power station in Europe [42]. ACS Cobra Energy is the owner and manager of the facility. In order to liquefy the steam once more, the plant uses a wet cooling system. It also has a thermal storage system with a capacity of 1 GWh, which allows it to generate electricity for around 7.5 hours under normal conditions while storing some of the heat produced by the solar field during the day in a molten salt combination. The primary design parameters utilized in the simulation of the reference plant "Andasol-1," taken from reference [43], are listed in Table 1.

Table 1. Main features of the reference CSP plant (Andasol-1 project) [43].

Parameter	Value
Solar Field aperture	510120 m^2
Working fluid in receiver tubes (HTF)	Dowtherm A
Design loop inlet temperature	296 °C
Design loop outlet temperature	393 °C
Type of solar collector	EuroTrough ET150
Aperture width	5.76 m
Focal length	1.71 m
Number of collectors per loop	6
Number of loops in the solar field	156
Type of receiver	Solel UVAC3
Glass envelope inner diameter	0.115 m
Glass envelope outer diameter	0.121 m

Absorber tube inner diameter	0.066 m
Absorber tube outer diameter	0.07 m
Nominal gross electric power	55 MWe
Rated cycle conversion efficiency	0.381
Full load hours of TES	7.5 h
Fluid in the 2-tank TES	Solar salt
Tank height	14 m
Dispatch Schedule	Summer Peak

The optimization process was carried out using a parametric simulation technique. Giving one or more input variables numerous values during a parametric simulation to assess how much the results depend on the inputs.

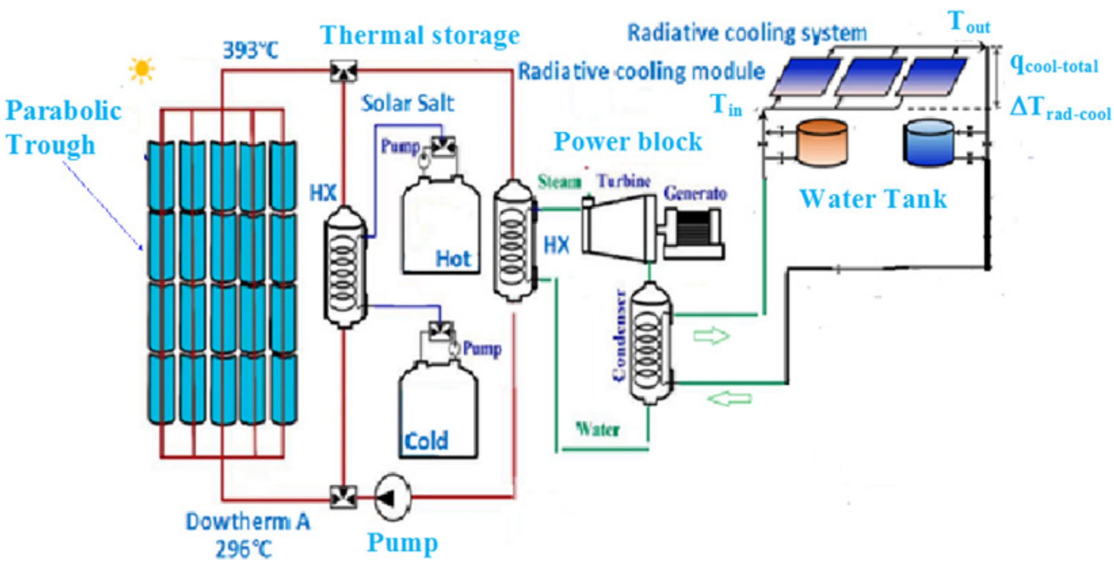

Figure 5. Indirect Parabolic Trough power plant with two tanks storage thermal energy and the proposed radiative cooling system.

3.2. Economic aspects

SAM software has been used to confirm the impact of the use of a radiative cooling system at the Levelized Cost of Energy and Total Installed Cost of a Parabolic Trough Concentrating Solar Power Plant. Table 2 lists the economic and low-cost factors that were employed during the experiment.

Table 2. Economical and financial parameters used in the simulation.

Parameter	**Value**
Site improvement	25 $/m2
Solar Field	150 $/m2
Working fluid (HTF) system	60 $/m2
Storage system	62 $/m2
Power plant	910 $/m2
Balance of plant	90 $/m2
Analysis period	30 years

Inflation Rate	1.95 %/y in 2021 [44]
Real Discount Rate	5.59 %/y in 2021 [44]
Nominal Discount Rate	7.65 %/y
IRR target	11 %
Sales Tax	5 % of the installed cost
State Income Tax Rate	7%/y
Developer Capital Recovery	3 years

Table 3 represents the main design parameters of the radiative cooling system used in the simulation.

Table 3. Design parameters of the radiative cooling system used in the simulation.

Parameter	Value
The inner diameter of the radiator tube	0.02 m
The thickness of the radiative module	0.002 m
Length of row of radiative modules	100m
Length of individual radiative modules	10 m
Emissivity of the radiative module	0.95
Equivalent full load hours of cold storage	15 hr
Mass flow through a single module	8 kg/s
Cold storage tank height	30 m
Cold tank initial temperature	10°C
Conductivity of module	235 W/m-K

3.3. Environmental aspects

The land area used for project development, its annual water consumption, and its annual carbon dioxide emissions are known to be the most important environmental factors that should be taken into account in every business industry [45]. One of the options that has the potential to influence power plants' ability to reduce CO2 equivalent emissions and their life cycle assessment is the condenser cooling system. On the amount of land and water used annually, cooling technologies may potentially have negative effects. The three cooling structures' effects on the environment were examined in this section of the study in terms of annual water use and land area.

The Greenhouse Gas Emission (GHG) and Life Cycle Assessment (LCA) analyses of this technology cannot be determined because long-term functioning results are nonexistent.

3.4. Evolution of the techno-economical-environmental performances

Utilizing a radiative cooling system has two advantages: it lowers annual water and energy expenditures while enhancing plant efficiency. Additionally, a CSP plant's condenser cooling system selection necessitates taking into account a number of factors (technological, economic, and environmental). Therefore, the reference plant at the Tamanrasset site, where the CSP plant was more suited, was used to model the influence of cooling system parameters on the techno-economic-environmental performance of PTCSTPP under the same input, using the parameters of Tables 1, 2 and 3. The results are provided in Table 4 for several meteorological parameters at the site that were gathered from various research [38][46].

Table 4. Performance of SAM model with same Andasol-1 inputs Tamanrasset.

Performances	Wet cooled	Dry cooled	Radiative cooled
Technical Performances			
Full Load Hours	7.5	7.5	7.5
Capacity Factor (%)	58	53	59
Annual Energy (MWh)	253.42	231.07	259.81
Economic performances			
Levelized Cost of Energy (¢/kWh)	9.79	10.74	9.55
Total Installed Cost (Million$)	309.77	309.77	309.77
Environmental Performance			
Annual Water use (m^3)	817152	45907.4	45942.3

These findings, along with an initial comparison of wet and dry cooling structures, make it clear that a significant amount of power can be produced using a wet-cooled condenser with a lower energy cost and excessive performance due to the use of additional power sources in dry-cooled electricity plants. The wet cooling system requires a large amount of water compared to other cooling systems, causing an annual increase of 771209.7 m3 due to considerable water losses from continuous evaporation inside the cooling tower, which proves that this mechanism needs a constant supply of water. The dry cooling system is dependent on the dry-bulb temperature, allowing the plant to use less water. In order to attain the same techno-economical-environmental performances of a plant with a wet-cooled condenser and the same amount of water that is used in a dry-cooled condenser, the radiative cooling system will be used. Due to the high parasitic loads for dry-cooled condensers within that radiative cooling system and a reduction in water use with the aid of using 771209.7 m3 in comparison to a wet cooling system, it is an appealing option for arid regions. Therefore, the power production has been increased by nearly 11% in comparison to a dry cooling system. As a result, the radiative cooling system has a very high potential for energy savings with no energy expenditure. Furthermore, the wet cooling system requires additional infrastructure and additives, including a water delivery network, evaporation ponds, storage ponds, and a sizable treatment plant for the condenser cooling water. It has also been found that the energy cost of this cooling system is the lowest in comparison to others. However, a dry cooling system needs a lot of metal and aluminum in significant numbers. Finally, radiative cooling offers among other things a particularly alluring solution for CSP units. The fact that the average established cost of any plant remains constant shows that it depends on a variety of factors, including plant capacity, solar field area, and the quantity of collectors.

Table 5. Effect of solar field size on water use in Tamanrasset.

Total Solar Aperture (m^2)	Radiative cooling	Evaporative cooling	Dry cooling
400000	37729	696224	37701
420000	39558	729826	39537
440000	41467	765845	41441
460000	43264	798058	43235
480000	45084	831194	45056
500000	46771	859415	46730
520000	48763	893388	48712
540000	50293	916469	50210
560000	51579	931235	51490

580000	52878	946445	52742
600000	54073	958698	53945

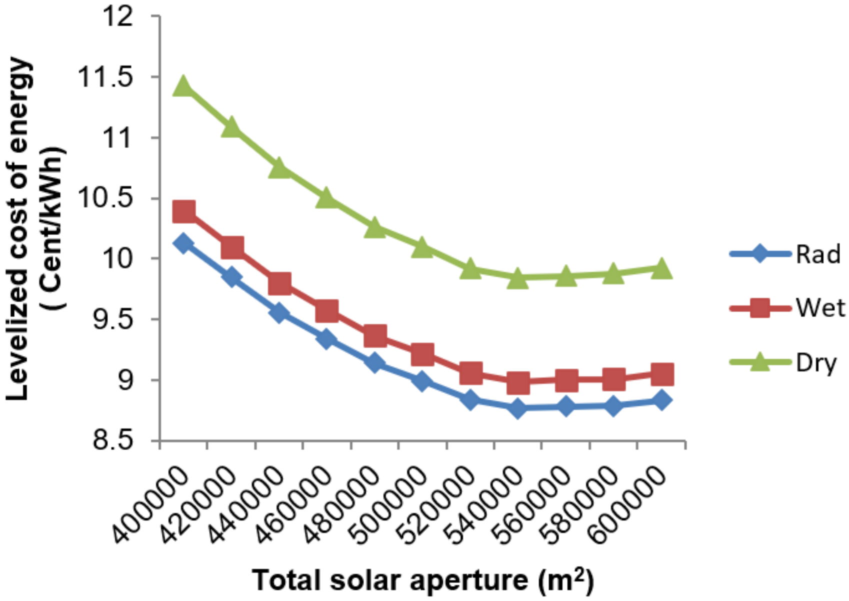

Figure 6. Effect of solar field size on the levelized cost of energy in Tamanrasset.

From the results, it's clear that the increase in solar field size, the increase levelized cost of energy for all cooling technologies until an optimal value when the parasitic loads and total investment cost increase for a large solar field. Moreover, the levelized cost of energy is low in the case of radiative cooling among others.

3.5. Site parameters effect

Three places that correlate to Algeria's desert—Hassi Rmel, Insalah, and Bechar—have been chosen for this study in order to examine the impact of various meteorological circumstances on the performances of PTCSTPP with a radiative cooling system. Table 6 shows the annual Direct Normal Irradiation (DNI), ambient temperature, and wind speed for such locations. Hassi Rmel, Insalah, and Bechar are located at latitudes of 33.8°, 27.8°, and 29.24°, respectively. The chosen locations are typically found in the sun-belt regions, between latitudes of 15° and 40°, where it is feasible for CSP facilities to operate profitably. The most crucial component for installing a CSP plant is direct normal irradiation, which needs to be greater than 1900 kWh/m2/year. With a value of 2611, 2570, and 2008 kWh/m2/year, respectively, Bechar has the greatest DNI, followed by Insalah and Hassi Rmel as shown in Table 6. These numbers are significantly higher than 1900 kWh/m2/year, showing that these locations would be better suited for profitable CSP facilities. The average ambient temperature is depicted in Table 6. It is clear that the chosen locations are in sweltering climates where the heat-transfer fluid cannot freeze.

Table 6. Meteorological parameters of the selected sites [47].

	Direct normal irradiation (kWh/m2/Y)	Average ambient temperature (°C)	Average wind speed (m/s)
Hassi Rmel	2008,4	16,7	4,6
InSalah	2570,3	25,6	5,2
Bechar	2611,1	24,5	4,3

Table 7 provides the findings of the impact of various parameters. As can be seen, technological and economic performance directly relates to geographic and climatic factors (DNI, ambient temperature, and relative humidity), with the highest DNI site (Bechar) producing the best results. The amount of water used annually was also raised by the high ambient temperature. Due to sandstorms in the desert regions, which can be parasitic, the wind speed is higher in all locations where additional water is needed to clear the mirror.

The direct normal irradiation, wind speed, and ambient temperature all affect how much water the radiative cooling system uses. In conditions of low ambient temperature, little wind, and high DNI, it grows larger. Finally, the regional meteorological and geographical characteristics of the site affect how well a radiative cooling system performs.

Table 7. Effect of site parameters on the performance of PTCSTPP with a radiative cooled condenser.

Performances	Hassi Rmel	Insalah	Bechar
Technical Performance			
Full Load Hours	7.5	7.5	7.5
Capacity Factor (%)	44	59	60
Annual Energy (MWh)	191.41	260.23	264.64
Economic performance			
Levelized Cost of Energy (¢/kWh)	12.97	9.54	9.38
Total Installed Cost (Million$)	309.77	309.77	309.77
Environmental Performance			
Annual Water use (m^3)	39988.2	45966.6	46347.9

3.6. Storage system effect

This section examined how the size of the STE system affected the operation of the PTCSTPP with a radiative cooling system at the Tamanrasset location using a fixed solar field size. Between 2 and 15 hours make up the Full Load Hours (FLH). The simulation's ideal outcomes are shown in Table 8.

Table 8. Effect of STE on the performance of PTCSTPP with the radiative cooled condenser in Tamanrasset.

FLH	CF (%)	Annual Energy (MWh)	LCOE (¢/kWh)	Total Installed Cost (Million$)	Annual Water (m3)
2	47	259.82	9.64	244.29	41082.9
4	54	259.82	9.1	268.11	43907.2
6	58	259.82	9.18	291.92	45550.8
7.5	59	259.82	9.56	309.78	45942.3
8	59	259.82	9.7	315.73	45997.9
10	59	259.82	10.39	339.55	46030.2
12	59	259.82	11.10	363.36	46001.2
13	59	259.82	11.47	375.27	45984.7
14	59	259.82	11.83	387.17	45967.8
15	59	259.82	12.19	399.08	45951.4

The results show that the cost of energy and the total installed cost rise as FLH grows, confirming that the economic performances are often influenced by the size of the STE system. Additionally, while the solar field size does not change, the other performances are unaffected by the changing STE system size.

3.7. Plant nominal gross electric power effect

In order to examine the behavior of this plant with an excessive nominal gross electric power, the performances of a 100 MWe PTCSTPP with three cooling structures were simulated using the equal inputs of Parabolic trough plant Ilanga 1, Upington, Northern Cape, South Africa, inside the Tamanrasset site. Table 9 presents the outcomes.

Ilanga 1 is a 100 MWe thermosolar plant with 266 SENERtrough® parabolic trough loops that was created and patented with the help of SENER. It has a 1,250 MWth capacity for molten salt heat storage. Table 9 lists this plant's primary functions.

Table 9. Main features of Ilanga- 1 plant [48].

Parameter	Value
Technology	Parabolic trough collector, SENERtrough®.
Solar Field aperture	869,800 m^2
Number of loops in the solar field	266
Nominal gross electric power	100 MWe
Full load hours of STE	5 h
Working fluid in receiver tube (HTF)	Thermal oil
Full load hours of STE	4.5
Fluid in the 2-tank indirect STE	Molten salt
Cooling system type	Dry cooling

Table 10. Effect of plant nominal gross electric power in Tamanrasset.

Performances	Wet -cooled	Dry- cooled	Radiative cooled
Technical Performance			
Full Load Hours	7.5	7.5	7.5
Capacity Factor (%)	47	42	48
Annual Energy (MWh)	409.16	369.9	420.48
Economic performance			
Levelized Cost of Energy (¢/kWh)	11.27	12.47	10.97
Total Installed Cost (Million$)	574.36	574.36	574.36
Environmental Performance			
Annual Water use (m^3)	1344220	76754.5	76947.8

As shown in Table 10, the plant capacity has a significant impact on the overall installed cost. All results improve with an increase in this parameter, with the exception of plant efficiency, which fell due to a fixed STE system size. Additionally, when cooling systems were evaluated, the same comments as a 50 MWe PTCSTPP were discovered, and a CSP plant's cooling system is its primary water-consuming component.

The yearly water use for both systems is 76947.8 and 1344220 m^3, while the cost of energy for wet and radiative systems is 11.27 and 10.97 ¢/kWh, respectively. Given the amount of water utilized, the radiative system is more cost-effective and environmentally benign than the wet system in this regard.

More water is needed for larger plants. In this instance, doubling the plant's capacity would result in a more than 60 % increase in the water volume for all cooling technologies. Finally, parametric tests showed that radiative cooling is the most economically advantageous method for CSP facilities based on the aforementioned results.

4. RESULTS VALIDATION

Table 11 compares the optimal results of our three models utilizing the same Andasol-1 inputs at the Tamanrasset, Algeria location using three different cooling systems for actual Andasol-1 plant data.

Table 11. Comparison of results to real data of Andasol- 1

	Our model with Radiative cooled	Our model with wet-cooled	Our model with Dry-cooled	Andasol -1 [47]
Location	Tamanrasset-Algeria	Tamanrasset-Algeria	Tamanrasset-Algeria	Granada -Spain
DNI (kWh/m²/year)	2759.4	2759.4	2759.4	2260
Technology	Parabolic Trough	Parabolic Trough	Parabolic Trough	Parabolic Trough
Capacity (MW)	50	50	50	50
Cooling system type	Radiative	Wet cooling	Dry cooling	Wet cooling
HTF	Dowtherm	Dowtherm	Dowtherm	Dowtherm
Medium Storage	Molten salt	Molten salt	Molten salt	Molten salt
SM	1.7	1.7	1.7	1.7
FLH(h)	7.5	7.5	7.5	7.5
LCOE (¢/kWh)	9,55	9.79	10.74	18.55
Total Installed cost (Million$)	309.77	309.77	309.77	411.69
Capacity Factor (%)	59	58	53	41
Annual water usage (m3)	45942.3	817152	45907.4	612000
Annual Energy (MWh)	259.81	253.42	231.07	179.1

5. CONCLUSION

In this study, SAM software is used to analyze and validate the best performance of a parabolic trough-concentrating solar thermal system with a radiative cooling system in comparison to the "Andasol-1" reference system. For plant parameters, data from the Andasol-1 experiment that were published in the literature were used. The outcome is displayed below:

The radiative cooling-based parabolic trough-concentrating solar power plants can use less cooling water.

The type of condenser cooling technology employed, the local meteorological conditions (ambient temperature, typical direct irradiation, and wind speed), variation in system capacity, and the size of the storage system all play a role in how well a parabolic trough concentrating solar thermal system performs. When compared to dry cooling technology, the evaporative cooling system had the best overall performance results. In this study, compared to dry and wet cooling structures, the radiative cooling mechanism boosted the annual electricity output by approximately 11 % and 2.4 %, respectively.

Radiative cooling consumes only half as much water as wet cooling, which means it doesn't require a constant supply. Furthermore, the efficiency of radiative cooling can function at temperatures near to or below ambient, whereas the effectiveness of dry cooling is restricted by the ambient dry bulb temperature of the dry bulb. In order to attain the same performance as a wet-cooled condenser and the same water consumption as a dry-cooled condenser, radiative cooling may be used.

More water is needed for larger plants. In this instance, doubling the plant's capacity would result in a more than 60 % increase in the water volume for all cooling technologies.

The environmental assessment found that dry cooling used 771209.7 m3 less water annually than wet cooling, with a potential yearly water savings of more than 50 %, making it a desirable option for arid environments.

Because this cooling system requires more additives, such as a water delivery network, evaporation ponds, storage ponds, and a sizable treatment plant for condenser cooling water, its LCOE was determined to be 9.55 ¢/kWh, making it the least expensive cooling system when compared to others. But for dry cooling, a lot of metal and aluminum is needed.

According to the results of the sensitivity analysis, the performance of the radiative plant is directly correlated with the amount of DNI, with the proper outcomes being completed at the best DNI site. Additionally, the high ambient temperature increased the amount of water used annually. Due to sandstorms within the desert regions, high wind speeds result in an excess of water needed for cleaning mirrors.

Finally, parametric investigations determined that radiative cooling, as examined in this paper, is the most economically advantageous solution for the next generation of CSP plants located in arid and desert climates among all novel cooling technology, primarily based entirely on the aforementioned results.

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6. ABBREVIATIONS

LCOE	Levelized Cost Of Energy
CSP	Concentrating Solar Power
SAM	System Advisor Model
NREL	National Renewable Energy Laboratory
PTCSTPP	Parabolic Trough Concentrating Solar Thermal Power Plant
DLR	German Aerospace Centre

DNI	Direct Normal Irradiation
TMY	Typical Meteorological Year
HTF	Heat Transfer Fluid
TIC	Total Installed Cost
RES	Renewable Energies
SM	Solar Multiple
AW	Annual Water
AE	Annual Energy
TIC	Total Installed Cost
CF	Capacity Factor
SF	Solar Field
PB	Power Block
TES	Thermal Energy Storage
SCA	Solar Collector Assembly
HCE	Heat Collection Element
I_{bn}	Direct Normal beam
Q_{collec}	Collected heat
Q_{absor}	Receiver Absorbed heat
T_{db}	Temperature of the dry air
$\dot{q}_{rej}$	Heating load
P_{net}	Net cooling power
P_{rad}	Sum of radiative emission from the cooler
P_{sol}	Absorption of solar irradiation
P_{atm}	Atmospheric emission
P_{con}	Heat input through conduction and convection
T_s	Temperature of the surface
NSCA	Number of the collector in the field
η_{geo}	Geometric efficiency
η_{opt}	Optical efficiency
η_{iam}	Incidence angle modifying
η_{th}	Thermal efficiency
η_{field}	Field efficiency
$A_{ap,tot}$	Total aperture area
$T_{sf,in}$	Solar field inlet Temperature

$T_{sf,out}$	*Solar field output Temperature*
T_{amb}	*Ambient Temperature*
I_0	*Investment expenditures*
At	*Annual total costs in year t*
Mt, el	*Produced quantity of electricity in the respective year in kWh*
i	*Real interest rate in %*
n	*Economic operational lifetime in years*
t	*Year of a lifetime (1, 2, ...n)*
m_w	*Water mass in the module in kg*
m_{pc}	*Empty mass of the module in kg*
m_{cw}	*Actual cooling water mass flow rate through the power plant condenser in kg/s*

7. GREEK LETTERS

ε_s	*Emissivity*
α_s	*Absorptivi of a radiative cooler*
ρ_s	*Reflectivity of the radiative cooler*
ε_{atm}	*Emissivity of the atmosphere*
$\tau_{atm}(\lambda)$	*Spectral transmissivity of the atmosphere*