# Impact of Ground Heat Source Addition on Main Performance Parameters of Solar Chimney Power Plants: A Numerical Study

Erdem Cuce[1,2,3,*] and Siddig Omer[4]

[1]Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey

[2]School of Engineering and the Built Environment, Department of Mechanical Engineering, Birmingham City University, B4 7XG, Birmingham, UK

[3]Center for Research Impact & Outcome, Chitkara University, Rajpura-140401, Punjab, India

[4]Department of Architecture and Built Environment, University of Nottingham, NG7 2RD Nottingham, UK

**Abstract:** Solar energy systems can be an alternative to fossil fuels and are vital for a sustainable environment. It is promising that solar chimney power plants (SCPPs), which are among the solar energy systems, provide 24-hour power output (PO) and can work integrated with other systems. This study is based on the Manzanares pilot plant (MPP) and demonstrates satisfactory performance with an additional heat source to be integrated into the ground of the system during hours when solar radiation is weak. The performance of the system at different source temperatures is compared with the reference case, with the model verified using the RNG k-ε turbulence model through a 3D CFD study. In fact, it is seen that the PO of the system, which yields a PO of around 10 kW at 200 W/m$^2$ solar radiation in the reference case, exceeds 80 kW with a source temperature of 200°C. From the results, it can be noticed that the system can also output power in the evening hours when there is no sun. With an additional heat source of 200°C during non-sunlit hours, the system gives more than 75 kW PO. This PO is 50% more than the maximum PO of 50 kW in the reference case.

**Keywords**: Solar chimney power plant, Hybrid solar chimney, Waste heat source, Performance assessment, Power output

## 1. INTRODUCTION

Energy consumption, which increased with the Industrial Revolution, keeps rising day by day. In addition, with the increasing human population, individual energy consumption also becomes important. Energy production, which is based on fossil fuels, continues to keep popular issues such as environmental pollution and carbon emissions on the agenda daily, along with increasing consumption. If the widespread use of fossil fuels is not prevented, it seems that environmental pollution will not only threaten human life but also lead to permanent natural disasters in the coming period. Buildings are responsible for most of the world's energy consumption [1]. Although the target of reducing the carbon emission level by 20% in 2020 compared to 1990 is targeted by international protocols, it is a matter of debate whether the desired level has been reached [2]. Considering the increasing human population and the rate of industrialisation, it is highly likely that fossil fuels will continue to be used. However, efforts to meet energy needs with renewable energy sources are increasing day-to-day. Renewable energy sources are clean energy sources and are a great alternative to fossil fuels as they do not emit any emissions during the performance phase and are environmentally friendly [3]. Hydropower has the potential to be a great alternative to fossil fuels with its variety of renewable energy sources, which can be classified as biomass, solar, wind and geothermal [4]. Although renewable energy sources are diverse, it may not be possible to benefit from them in the same region. The reason for this is that some of them only allow use in certain geographical regions. In addition, the sun is an unlimited energy source that can be used almost anywhere on Earth, regardless of region [5]. Solar energy has been used by humans since ancient times. It is ubiquitous to use it, especially for purposes such as space and water heating. It allows direct and indirect use of solar energy, allowing it to be used for different purposes. Electricity can be produced directly from the sun through photovoltaic (PV) systems, and its thermal energy can also be utilised. Special PV modules can use the solar radiation falling on them directly to generate electricity [6]. It is quite common to benefit from the thermal energy of the sun. This is because it can be used directly and does not require complex systems. The sun can be used effectively through transparent sections integrated into buildings for lighting and space heating [7]. Similarly, solar thermal energy can be used for water heating with different techniques [8]. Generating electricity from the sun requires complex systems other than PV modules. While electricity can be produced directly through PV modules, in order to generate electricity indirectly from the sun, the sun's thermal energy must be transferred to an intermediary fluid, and electricity must be

Address correspondence to this article at the Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize, Turkey; Tel: +90 464 2237518-1203; Fax: +90 464 2237514; E-mail: erdem.cuce@erdogan.edu.tr

 

produced from the intermediary fluid through a cycle. For this reason, solar energy systems may require technical infrastructure. Table **1** gives examples and details of systems that allow direct and indirect electricity generation from the sun.

Solar energy systems are solar dependent and their performance directly depends on solar radiation. In addition, in solar energy systems, systems other than PV systems transfer the thermal energy of the sun to the intermediary fluid, allowing electricity production by using additional systems. Although SCPPs are solar energy systems, they are privileged systems that provide PO during hours when solar radiation is weak or absent. SCPPs have a translucent collector that covers a large area. The solar radiation falling on a wide area is taken into the system by the transparent collector. Energy is transferred to the system air held under the collector by the solar radiation received into the system. In this way, the system air beneath the collector, whose temperature increases, constantly moves upward depending on the density difference. Solar radiation passing through the transparent collector reaches not only the system air but also the ground. The solar radiation reaching the ground is thermally stored here. This storage causes an increment in temperature. Thermal energy in the ground, whose temperature rises, is transferred by convection to the system air, where solar radiation is low and does not reach sufficient temperature, supporting the performance of the system. In addition, if there is sufficient energy storage in the ground, heat transfer to the system air occurs even during sunless hours, and a continuous upward movement of the system air is ensured. The system air continues its upward movement until the high chimney entrance located in the collector centre. SCPPs create a constant pressure difference due to the height difference at the inlet and outlet of the chimney in its structure. The vacuum effect created by this pressure difference evacuates the system air at the chimney entrance by accelerating it upwards from the chimney. Meanwhile, the kinetic energy of the system air is converted into PO through the turbine generator system located in the chimney. Although SCPPs are an old idea, the system is first implemented by a research team in Manzanares, Spain [16]. The diameter of the transparent collector of this system, which has a chimney height of approximately 200 m and an average height of 1.85 m, is approximately 250 m [17]. In addition to being the first application of the system, it is also very important in terms of putting the theory into practice. According to the measurements taken, it is reported that 50 kW PO is obtained from the system on a typical summer day, and the temperature of the system air under the collector increases by 20 K [18]. The Manzanares prototype pioneers research on the system. After the system produces results, researchers conduct numerous studies on performance parameters. The first studies on the system are in heat transfer analysis and are mainly theoretical. Mullet [19] makes a mathematical study on the overall efficiency of solar chimneys regarding design and performance. Manzanares argues that results parallel to the pilot plant data have been obtained and that the system will serve as a large-scale generator. It claims that the system efficiency is low, but 1% efficiency can be achieved with a chimney height of 1000 m. Low system efficiency is one of the biggest criticisms. The use of a collector that covers a large area in the system efficiency calculation is the biggest reason for the low system efficiency. In order to augment system performance and, therefore, system efficiency, researchers make recommendations for improving the system. Climatic and geometric parameters affecting system performance can be evaluated independently. Climatic parameters vary by region and cannot be intervened. Cuce et al. [20] use the MPP as a reference, they present a detailed analysis of the effects of climatic parameters, environmental temperature, and

**Table 1: Some Solar Energy Systems Examples for Electric Production**

| Ref. | System | Details |
|---|---|---|
| [9] | PV modules | The solar radiation falling on it is converted into electricity through special modules. |
| [10] | Solar tower | The sun's rays collected at the top of a tower by reflective mirrors are transferred to a cycle with the intermediary fluid to produce electricity. |
| [11-12] | Parabolic troughs | The solar energy collected at the centre of the parabolic solar concentrators is transferred to the fluid in the pipe located there. The fluid is then cycled, and electricity is produced. |
| [13] | Dish-engine | Electricity is produced with the Stirling engine placed at the centre of a large-sized concentrator dish. |
| [14] | Fresnel lens | With special lenses with high concentration capacity, solar energy is concentrated and transferred to the intermediary fluid. Then, the intermediary fluid is transferred to the cycle, and electricity is produced. |
| [15] | Solar chimney power plant | It transfers the solar energy it receives through a transparent collector to the system air inside. The air with increasing temperature is directed upwards and is evacuated from the system with the constant pressure difference created by the high chimney. During the evacuation process, electricity is produced by the turbine inside the chimney. |

solar radiation, on the system performance with a 3D computational fluid dynamic (CFD) study. They state that solar radiation intensity is very effective in improving system performance. They state that the system, which gives a PO of 17-18 kW at 400 W/m$^2$ solar radiation in the reference case, will give approximately 50 kW PO at 1000 W/m$^2$ solar radiation. They argue that the environmental temperature will have a detrimental impact on the PO. It is understood from the study that a system that is likely to be installed will give better performance in regions with high solar radiation and low environmental temperatures. There are also studies by different researchers in which they present that the system performance increases significantly due to solar radiation [21-22]. Some researchers also evaluate the effects of solar radiation and environmental temperature on system performance with experimental prototypes [23]. Climatic parameters are not related to the system design but are directly related to the region where the system will be installed. For this reason, even though researchers present the effects of climatic parameters on system performance in detail, performance improvement studies are mainly design-oriented. The effects of changes in geometric parameters and optimum sizing and design shapes on system performance should be evaluated in detail. To enhance system performance, increasing the chimney height is expected to be effective, as the chimney serves as the driving force of the system. Scholars examine the impact of chimney height on system performance with laboratory-scale systems [24]. They show that increasing the chimney height improves system performance. It is very difficult to make geometric evaluations with large-scale systems. The reason for this is that it is not possible to set up a different experimental setup for each dimensioning. For this reason, it is seen that researchers carry out geometric studies with theoretical, mathematical, or computational fluid dynamics (CFD) models. Cuce et al. [25], based on MPP measurements, discuss the effect of chimney height on system performance with a 3D CFD model. They posit that the system, which yields a PO of around 50 kW in the reference scenario, would generate a PO of 134 kW with a chimney height of 500 m. Similarly, other researchers also present their studies supporting that increasing the chimney height increases system performance [26, 27]. Although increasing the chimney height seems to consistently increase PO, there is a limitation to this situation. They claim that the maximum power that can be obtained by increasing the chimney height for the MPP is 102.2 kW, and that the optimum chimney height is 615 m [28]. Similarly, there are researchers who argue that increasing the chimney height for the MPP will not continuously increase the PO, and that the PO will decrease after 600 m [29]. A similar situation applies to the collector. Increasing the collector size will increase the energy entering the system, so performance is expected to increase. However, optimum sizing, such as chimney height, is expected. While it is argued that increasing the collector size will increase the PO of the system, and if the collector diameter is made 350 m, the PO will reach 175 kW for the MPP [30], there are also researchers who emphasise the limitation [31]. Researchers present studies showing system outputs at different sizes for chimney diameter and collector height [15]. Not only the sizing but also the different designs of the collector and chimney affect the system performance [32, 33]. Studies in the literature show that detailed analyses have been carried out for geometric optimisation. However, instead of using the system alone, using it integrated with other systems may be suitable for both system efficiency and obtaining different benefits from the system, not only PO. These systems, called hybrid systems, offer a great opportunity for sustainability for SCPPs that have low efficiency alone. So much so that solar chimneys can be used not only to generate electricity but also for different purposes. Natural ventilation can be provided in indoor environments without energy consumption by using solar chimneys [34]. By adding a solar chimney to PV modules, the temperature can be reduced, and performance can be improved by providing natural convection [35]. Jamali et al. [36] evaluate the performance of the hybrid system using semi-transparent PV modules as SCPP collectors. They show that the system can cool the average temperature up to 15°C by providing cooling in PV modules with the natural air movement provided by the chimney. They also claim that the system delivers 29% more PO than under normal conditions. There are also researchers who report that a similar cooling effect and performance increase will be achieved by integrating PV modules into the system floor [37]. PV module integration not only increases the efficiency of PV modules with its cooling effect, but also increases performance by providing additional heat to the system air under the collector. Using an additional heat source on the system floor is also an effective method. So much so that the use of idle heat sources can be a cost-free source for system performance. Many studies can be effectively implemented to improve system performance by using SCPPs as cooling towers to use the waste heat of a nuclear power plant [38], additional heat input from the system floor using a geothermal source [39], or even flue gas combination [40].

Solar energy is one of the most important candidates for reducing fossil fuel consumption because the source of solar energy is unlimited and has no usage costs. SCPPs for electricity generation from solar energy are gaining significant acceptance. It is quite possible to generate electricity from sunlight using a simple collector, turbine and chimney. A number of studies based on the MPP have been conducted to improve system performance, but these systems cannot be used when there is no sunlight. Therefore, interest in this area is rising. In this study, it is aimed to present a different perspective to the literature, examining the effect of additional heat sources that can be applied to the ground to increase system performance during periods without sunlight. The biggest difficulty of the system is that its performance is low, especially during non-daylight hours, and a satisfactory performance cannot be achieved in periods when there is no sunlight. Energy storage units that can be placed to obtain energy from the system outside of daylight hours may be a solution, but it should be noted that this may be costly for all systems. Therefore, in the study, the impact of the heat source placed under a 10 cm soil-gravel mixture on the ground was examined in detail. Possible performance outputs of the heat source at different temperatures are presented with a CFD study.

## 2. METHODOLOGY

This study focuses on evaluating the performance of SCPPs with an external heat source added under the floor. Based on the geometric measurements of the MPP, a 3D CFD model is developed using the student version of ANSYS engineering commercial software. The created model is revised to include two 90° symmetry planes in order to obtain an economic analysis. The schematic view of the system, boundary conditions, and solution procedure are given in Figure **1**. The MPP has a stack height of 194.6 m, a collector diameter of 244 m, a stack radius of 5.08 m, and an average collector load of 1.85 m [17]. The CFD model is created based on these measurements.

While modelling, a constant temperature boundary condition is applied 10 cm below the ground, assuming that the temperature on the ground will remain constant in the steady state. Turbine efficiency is taken as 0.8 in accordance with the literature [15]. Since the temperature of the air, which is the system fluid, increases by 20°C in the experimental data, the Boussinesq approach is accepted for the density considered appropriate in the literature [15, 18]. The material properties used and the properties of the system air details are given in Table **2**.

The analysis is done via FLUENT. In all analyses, it is assumed that the flow is turbulent and continuous, incompressible, 3-dimensional, and climatic parameters are constant. The continuity, momentum, and energy equations solved through simulation are as follows, respectively [41]:

a. Continuity equation

$$\nabla.(\rho\vec{v}) = 0 \tag{1}$$

b. Momentum equatio

$$\nabla(\rho\vec{v}\vec{v}) = -\nabla p + \left(\mu\left[(\nabla\vec{v} + \nabla\vec{v}^T) - \frac{2}{3}\nabla\vec{v}I\right]\right) + \rho\vec{g} \tag{2}$$

c. Energy equation

$$\nabla.\left(\vec{v}(\rho E + p)\right) = \nabla.\left(k_{eff}\nabla T - h\vec{J} + \left(\mu\left[(\nabla\vec{v} + \nabla\vec{v}^T) - \frac{2}{3}\nabla.\overrightarrow{vI}\right].\vec{v}\right)\right) \tag{3}$$

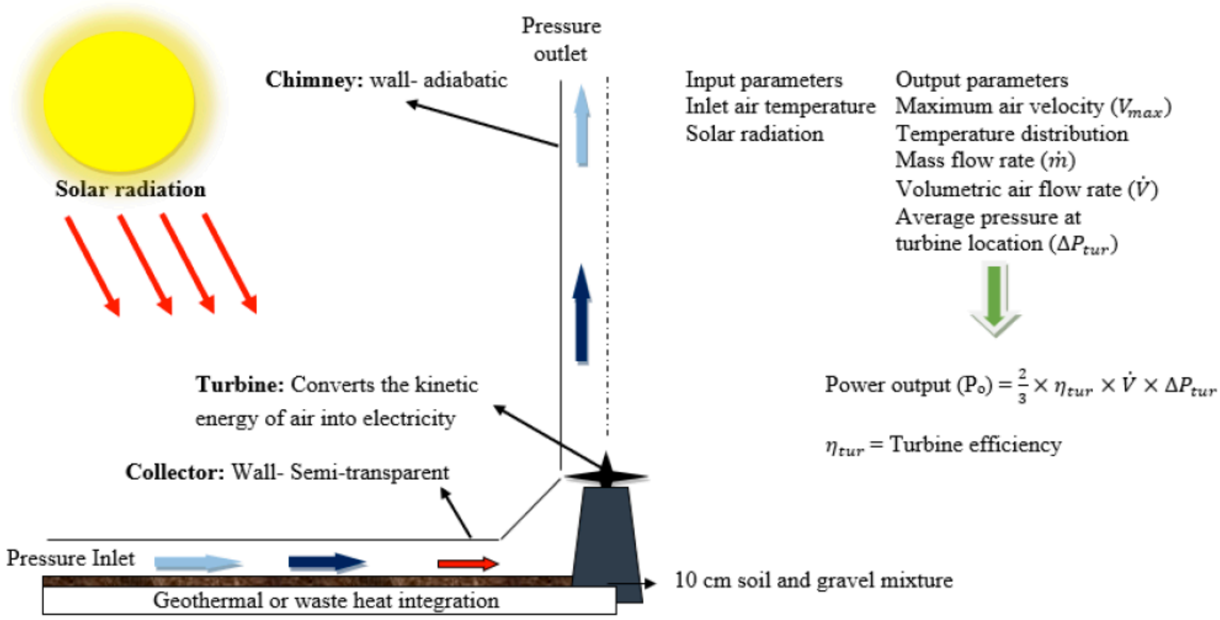


**Figure 1:** Schematic view of SCPPs and boundary conditions for CFD model.

**Table 2: Materials used in the System and Physical Properties of System Air [15]**

| Properties/Material | Chimney | Glass | Ground | Air |
|---|---|---|---|---|
| Density (kg/m$^3$) | 2100 | 2500 | 2160 | 1.176 |
| Heat capacity (J/kg) | 880 | 750 | 710 | 1006.43 |
| Thermal conductivity (W/mK) | 1.4 | 1.15 | 1.84 | 0.00242 |
| Dynamic viscosity (kg/ms) | - | - | - | 1.78x10$^{-5}$ |

Literature and Rayleigh (Ra) number are taken as basis when the flow within the system is considered turbulent. Since Ra, which is the critical dimensionless number for natural convection, is greater than $10^9$, which is the critical value for the MPP, the flow is considered turbulent, and the RNG k-e turbulence model, which gives the best results in rotating flows, is used in the analysis [15]. The Ra number equation and the equations of the turbulence model are as follows, respectively [42]:

$$Ra = \frac{g\beta\Delta T {H_C}^3}{\alpha\upsilon} \tag{4}$$

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right] + G_k + G_b + \rho\varepsilon - Y_M + S_k \tag{5}$$

$$\frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1_\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_e + S_\varepsilon \tag{6}$$

Finally, the equation of the Boussinesq approach is given below [43]:

$$(\rho - \rho_a)g \approx -\rho_a\beta(T - T_a)g \tag{7}$$

The discrete ordinates (DO) solar ray tracing option is used to model solar radiation. Sun ray tracking algorithm: By entering the location of the MPP, the actual sun ray angle is entered from the solar calculator. Solution method SIMPLE for Pressure-Velocity Coupling Scheme, Green-Gauss Cell Based for Gradient in Spatial Discretion section and PRESTO for Pressure, first and second order upwind mixed is preferred. As a convergence criterion, $10^{-6}$ for momentum and energy and $10^{-3}$ for other options are considered sufficient. All analyses are made assuming the ambient temperature of 293 K is constant. Additionally, 200 and 1000 W/m$^2$ values are evaluated separately for solar radiation. This is done to evaluate the possible performance of the system in areas with low solar radiation. The temperature of the external heat source on the ground is applied as 50, 100, 150, and 200°C respectively, for comparison purposes for different temperature values.

## 3. RESULTS AND DISCUSSION

In this study, where the effect of using an additional heat source on the SCPPs floor is analysed on the system performance, a 3D CFD model is created, and firstly, mesh-independent solution and verification are performed. The created 3D model, the 90° model used for economy, and the mesh image are given in Figure **2**.

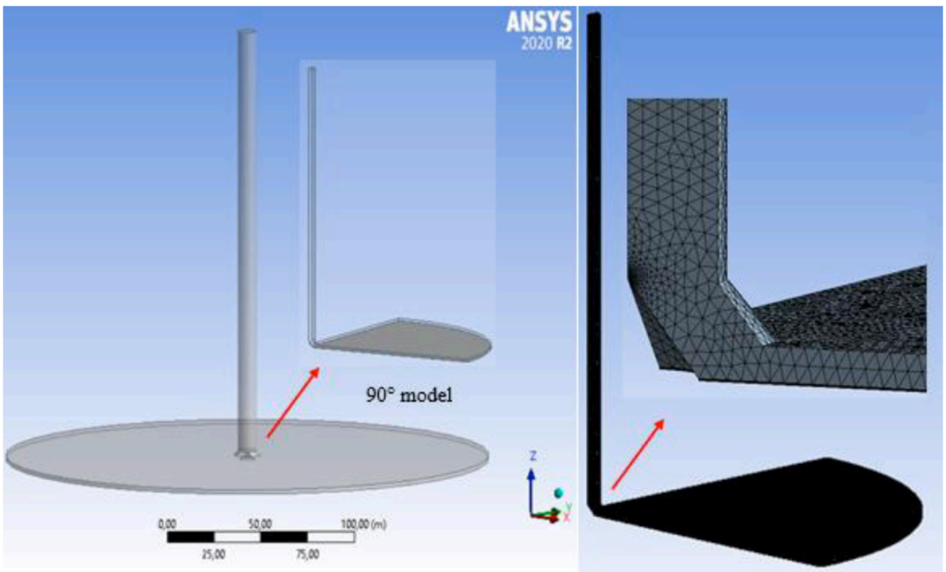


**Figure 2:** 3D model, 90° model used for economy, and mesh image.

In order to determine the independence of the mesh-independent solution study from the number of cells, the first created reference model is used to measure the change in PO for different cell sizes and cell numbers. When we look at the % changes according to the increasing number of cells, it is understood that the change for the 539650-cell number is negligible, and the solution for this cell size will be accepted. Details of PO and PO variation for different cell sizes and cell numbers are given in Table **3**. Once a mesh-independent solution is achieved, the model is validated. The verification process is done based on both experimental data and similar studies in the literature. For solar irradiance of 1000 W/m$^2$, experimental data from the MPP are taken as basis. Similarly, similar studies in the literature are compared for the same climatic conditions. Table **4** contains details of the comparison with experimental data and literature to validate the model.

After the mesh-independent solution and model verification are provided, simulations are started for the use of additional heat sources on the ground. The application of a heat source at different temperatures under a 10 cm thick soil gravel mixture on the ground is provided with a constant surface temperature boundary condition. The reason for this is that under continuous conditions, the temperature under the soil gravel mixture remains constant after a certain period of time. Comparison of the air velocity distribution in the system when a 200°C additional heat source is used on the ground at 293 K ambient temperature and 1000 W/m$^2$ constant solar radiation with the system without an additional heat source in the reference case is given in Figure **3**. The use of an additional heat source on the ground causes the additional heat to first pass to the soil and gravel mixture by conduction, and then to the system air by convection. In this process, as more heat will be transferred to the system air, the upward movement of the air is supported. While the maximum air flow rate in the system is 14.219 m/s in the reference case, when a 200°C additional heat source is used, the system's maximum air flow rate increases by 31.81% to 18.742. The PO graph for different additional heat source temperatures is given in Figure **4**. It is observed that the PO increases as the supplementary heat source temperature increases. This is due to the increase in heat transfer to the system with increasing source temperature. More PO can be obtained from the system by increasing the temperature of the additional heat source.

The main purpose of using an additional heat source is to aim for sustainability by obtaining PO from the system in low solar radiation or during times without solar exposure. So much so that the biggest handicap of solar energy systems is their inability to perform during non-sunny hours [46]. For this purpose, 24-hour PO can be obtained from the system with the additional heat source applied to SCPPs. In the reference case at 200 W/m$^2$ solar radiation intensity, the system gives a PO of approximately 10-11 kW. With the application of an additional heat source at 200°C ground, the PO from the system at the same solar radiation increases 8 times and reaches 82.391 kW. This means that even at low solar radiation, more PO can be obtained than the maximum PO that can be obtained in the reference condition. The effect of using an additional heat source

**Table 3: Mesh Independent Study for 3D CFD Model**

| Mesh size (m) | Elements number | PO (kW) | % change PO |
|---|---|---|---|
| 1.1 | 227918 | 46.11 | - |
| 1 | 293991 | 47.51 | 3.036 |
| 0.9 | 399302 | 48.725 | 2.55 |
| 0.8 | 539650 | 48.812 | 0.178 |

**Table 4: Comparison of CFD Model Results with Experimental and other Study Results in the Literature**

| Results | Max. air velocity (m/s) | Temperature rise in collector (K) | PO (kW) |
|---|---|---|---|
| **Experimental test results [18]** | 15 | 20 | 48 |
| **CFD results** | 14.219 | 18.958 | 48.812 |
| **% difference** | -5.2 | -5.21 | 1.69 |
| **Similar study from the literature [27]** | 16 | ≈20 | - |
| **Comparable research from the literature [45]** | 14.006 | 19.277 | - |

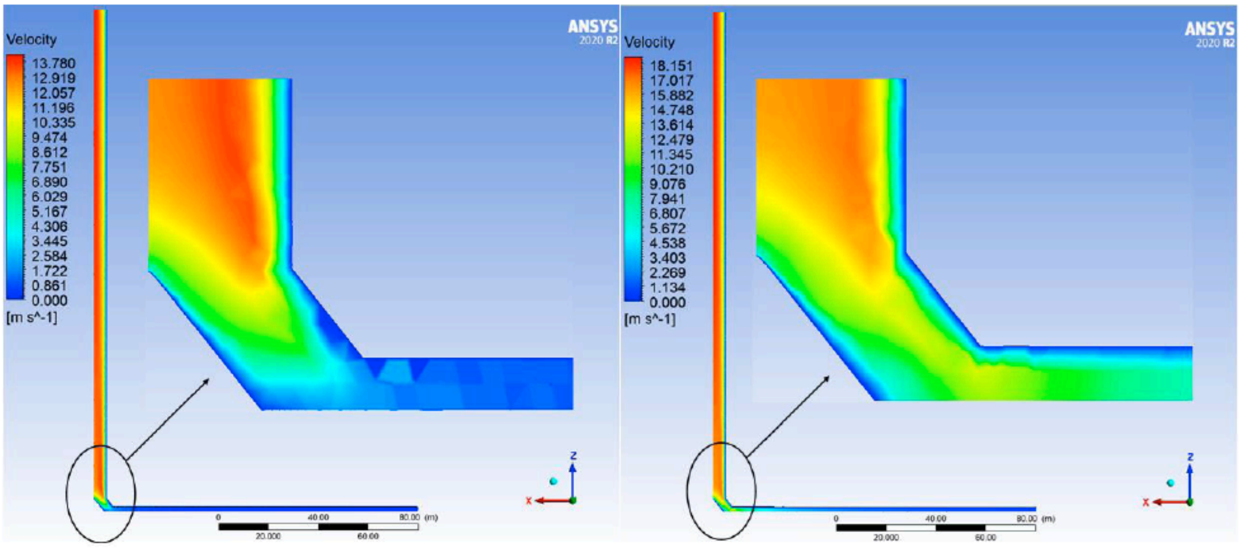


**Figure 3:** Air velocity in the system in the reference case at 1000 W/m$^2$ solar radiation and in the case of using a 200°C additional heat source on the ground.

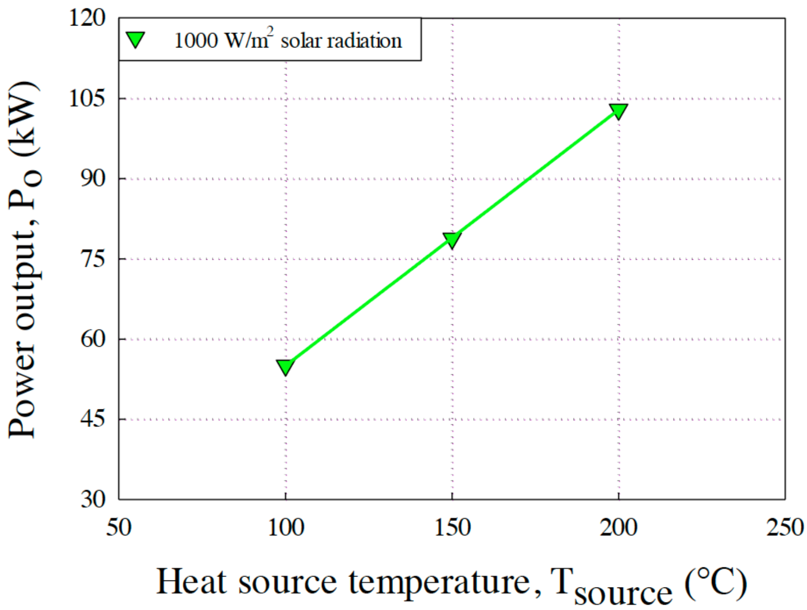


**Figure 4:** System PO for different additional energy source temperatures at 1000 W/m$^2$ solar radiation.

at different temperatures for 200 W/m$^2$ solar radiation on PO is given in Figure **5**. Additionally, it is seen in the graph that the use of an additional heat source without an energy storage unit on the ground allows PO during periods without sunlight. This makes the use of SCPPs attractive, especially for regions with high geothermal potential and limited sunshine duration. Even when there is no sun, it is seen that the PO exceeds 75 kW with the use of a 200°C additional heat source on the ground. Considering that the maximum PO in the middle of the day in the reference case is 50 kW, it is clear that the use of additional heat source on the ground provides a significant increase in system performance. Even the additional heat source at low temperature is sufficient for the sustainability of the system. However, solar radiation is the critical parameter for system performance in all cases. In subsequent studies, climatic parameters will be diversified and a more detailed analysis of the use of additional heat sources on the ground will be made.

## 4. CONCLUSIONS

SCCPs are a promising solar energy system for a sustainable environment and low emissions. The performance of these systems, which can provide 24-hour PO compared to other solar energy systems, can be improved with additional systems. In this study, the effect of using additional heat source on the ground on the system performance is evaluated using the 3D CFD model, taking the MPP as a reference. The

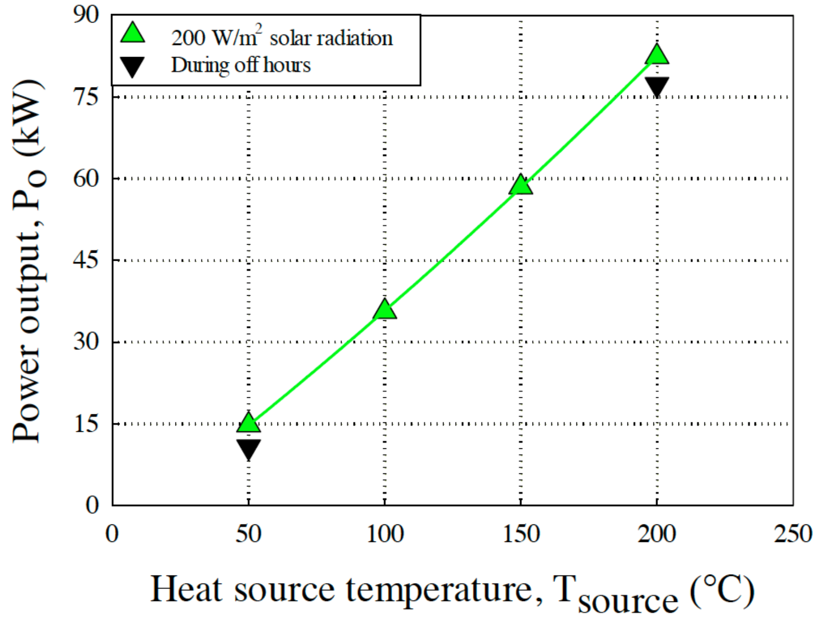


**Figure 5:** System PO for different additional energy source temperatures at 200 W/m$^2$ solar radiation and during off hours.

following critical findings are obtained in the analyses performed by simultaneously executing the RNG k-ε turbulence model and the discrete ordinates (DO) solar ray tracking algorithm:

- The 3D CFD model for SCPPs analysis gives results consistent with experimental data.
- The MPP gives a PO of 48.812 kW at 293 K ambient temperature and 1000 W/m$^2$ solar radiation. This value is very close to the experimental data of 48 kW.
- The use of waste heat in the ground increases the system performance. So much so that the PO, which is 48.812 kW at 1000 W/m$^2$ solar radiation in the reference case, increases by 110% to 102.955 kW with the use of 200°C waste heat on the ground.
- PO can be obtained from the system by using an additional heat source on the ground during hours when there is no sun. A PO of 10.792 kW can be obtained from the system with a 50°C additional heat source, and 77.306 kW with a 200°C additional heat source.
- Using an additional heat source on the floor increases system performance and allows PO during times when the sun is absent. However, solar radiation has an impact on PO.

## NOMENCLATURE

| | |
|---|---|
| SCPPs | Solar chimney power plants |
| CFD | Computational fluid dynamic |
| PO | Power output |
| MPP | Manzanares pilot plant |
| $C_p$ | The specific heat capacity (J/kgK) |
| $g$ | Gravitational acceleration (m/s$^2$) |
| G | Solar radiation (W/m$^2$) |
| $P_o$ | Power output (W) |
| $T$ | Temperature (K) |
| $T_a$ | Ambient temperature (K) |
| $\Delta P_t$ | Average pressure at the turbine location (Pa) |
| $\dot{V}$ | Volumetric flow rate (m$^3$/s) |
| $\dot{m}$ | mass flow rate (kg/s) |
| $\Delta T$ | Temperature difference |
| $H_c$ | Collector height (m) |
| $T_{HS}$ | Heat source temperature (°C) |

## GREEK LETTERS

| | |
|---|---|
| α | Thermal diffusivity (m$^2$/s) |
| $v$ | Kinematic viscosity (m$^2$/s) |
| $\beta$ | Thermal expansion coefficient (1/K) |
| $\eta_{tur}$ | Turbine efficiency |
| $\rho$ | Density (kg/m$^3$) |
| $\rho_a$ | Ambient density (kg/m$^3$) |

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