Impact of chimney design on maximum velocity in SCPPs

A critical review

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Abstract: Solar chimney power plants (SCs) are sustainable solar energy systems that offer the opportunity to generate electricity from the sun, which is a clean energy source. The system is remarkable with its simple structure consisting of a collector, chimney, and turbine and its operating principle based on basic physical laws. It transfers the solar radiation it receives to the system air in its structure with its semi-transparent collector, then upward air movement is observed depending on the density difference. The vacuum effect of the chimney, which is in the collector centre and creates a constant pressure difference due to its height, accelerates and discharges the upward moving system air. Meanwhile, the turbine inside the chimney uses the kinetic energy of the system air to generate electricity. The system is affected by climatic and geometric parameters. After addressing the operating principle of the system in this study, a perspective is presented from the studies in the literature regarding the height, diameter, and design of the chimney, which is one of the structural elements. In particular, the effect on the system power output is evaluated and performance estimates are made for the potential plants to be established. Comparative details are presented from the analyses made for the Manzanares pilot plant, and a basis is created for subsequent studies.

Keywords: Solar chimney power plant, Chimney design, Chimney effect

1   Introduction

Energy use is increasing day by day due to the increasing human population and technological developments. In addition to the technological developments in the last century, the spread of thermal comfort to the public has brought energy consumption to a different point. People consume energy not only in their homes but also in their work environments with demands such as lighting, heating and cooling. The biggest

problem at this point is which sources of energy are used. Rapid industrialization after the industrial revolution pushes states to use fossil fuels intensively. The widespread use of fossil fuels is seen as a problem in large circles, and especially environmental pollution and CO_2 emissions that endanger human life put countries on alert (Moosavian et al., 2024). The targets that countries set and protocols they put into effect more than 20 years ago to prevent environmental pollution due to the use of fossil fuels do not seem to have been successful yet (Cary and Stephens, 2024). Despite all this pessimistic picture, it would be wrong to say that there are no new approaches. In particular, the search for energy sources that can be alternatives to fossil fuels continues intensively. The biggest candidate in this regard is renewable energy sources. Renewable energy sources, which are spread over large areas and have a wide variety compared to fossil fuels, offer an unlimited potential, as the name suggests. These energy sources, which are also called alternative energy sources because they are used as an alternative to fossil fuels, are quite diverse such as solar, wind, hydroelectric, and biomass. In addition to the high potential of alternative energy sources, it is quite attractive that more than one can be used in the same region. When we look at the last 10 years, it is seen that energy production based on renewable energy sources is constantly increasing and especially the share of solar energy in this production continues to increase every year (Adhikari et al., 2024). When the sun is considered in terms of its potential and accessibility, it is the focus of alternative energy sources. The increase in solar energy research and technological developments in recent years play a critical role in the formation of this situation. The sun is the only source of life that can be used directly and indirectly for different purposes. The best examples of the direct use of solar energy are space and water heating. Solar energy, which has been used for these purposes since ancient times, is today effectively used especially for buildings. Nowadays, with new approaches, heating and cooling activities are carried out in buildings through solar energy (Suhendri et al., 2024). Solar energy, which is also widely used for water heating, is highly effective (Eze et al., 2024). There are many different areas of use of the sun not only for water and space heating but also for energy production. This application of the sun, which allows electricity production directly with photovoltaic (PV) modules, is used as broadcast (Cuce et al., 2017). There are different systems that allow electricity production from the sun indirectly. These systems concentrate solar energy to a point and use this energy, which they transfer to an intermediary fluid, to produce electricity through a cycle. Table 1 provides systems and technical details that can produce electricity directly and indirectly from the sun.

The common feature of solar energy systems, except for PV systems, is that they generate electricity by transferring solar energy to an intermediary fluid. Therefore, these systems can also be called systems that generate electricity indirectly from the sun. The high initial investment cost and high technology requirements of these systems make them difficult to establish. Solar chimney power plants (SCs) can generate electricity directly from the solar energy they receive. In this respect, they differ from other solar energy systems. The system is promising for solar energy systems with its simple structure and operating principle based on basic physical laws. In this study, the operating principle and technical details of SCs, whose first application does not

date back to very old times, are first included. Then, after the system performance critique is made, the change in the maximum air flow rate in the system depending on the chimney size and design is evaluated. Unlike the compilations in the literature, the effect of the change in the chimney configuration on the system performance parameters is evaluated together while the optimum situation analysis is also performed.

TAB. 1 : Systems that can produce electricity directly and indirectly from the sun and their technical details.

Reference	System	Details
Karaağaç *et al.*, 2024	Parabolic trough solar collectors	Sun is concentrated on a cylindrical tube placed at the focus of a parabolic bowl, and steam is obtained at high temperature and pressure. This steam is then used to generate electricity.
Ntegmi *et al.*, 2025	Dish-Engine Stirling system	Solar energy concentrated in the centre of a dish is used to generate electricity by a Stirling engine.
Sobic v *et al.*, 2025	Solar tower power plant	Many mirrors concentrate solar energy at the top of a tower. The solar energy collected at the top of the tower is transferred to a working fluid and used to generate electricity in a fluid cycle.
Cuce and Cuce, 2014	Photovoltaic (PV) systems	Modules manufactured for special purposes generate electricity directly from the sunlight falling on them.
Cuce *et al.*, 2022a	Solar chimney power plants	Solar energy it receives through the semi-transparent collector heats the system air. Electricity is generated through the turbine from the system air that is accelerated by the vacuum effect created by the high chimney.

2   Solar Chimney Power Plants

2.1   History and Working Principle

SCs is a system that operates according to basic physical laws and has a much simpler structure than other solar energy systems. The system has 3 basic structural elements : a semi-transparent collector, a high chimney, and a turbine. Leonardi da Vinci first theoretically mentions the system and creates a simple diagram (Dhahri and Omri, 2013). Much later than the first model presented theoretically, an effort to produce electricity from the system was seen. German engineer Prof. Schlaich and his team carried out an experimental installation in the Manzanares region of Spain and electricity was produced from the system for the first time (Schlaich et al., 2005). The system is of great importance in terms of being the first application and putting theory into practice. The system, which has a chimney height of approximately 200 m, has an average collector height of 1.85 m and a collector with a radius of 122 m, 6000 m^2 of glass and plastic (Haaf et al., 1983). The first facility is of great importance especially in terms of introducing the system and shedding light on subsequent studies. Theoretically, the power output of the existing system is important in terms of bringing a different perspective to the researchers in the following periods and developing the system. After the Manzanares pilot plant was established, it gave the expected performance theoretically in the experimental measurements and 15 m/s maximum air speed and 20 K temperature increase under the collector were measured. In addition, it is reported in the experimental measurements that the system gave a maximum power output of 50 kW in the middle of the day (Haaf 1984). Although

the system is a solar energy system, it has a very different structure from other solar energy systems. The reason for this is that the system has a high chimney and creates a continuous vacuum effect due to the pressure difference at the inlet and outlet. The solar radiation falling on the semi-transparent collector can reach the ground. In the meantime, the solar radiation passing through the system air increases the temperature of the system air with the radiation effect. While some of the solar radiation reaching the ground is absorbed by the ground, some of it is reflected and reaches the collector again. This continuous reflection creates a greenhouse effect and increases the temperature of the system air, and the system air with increasing temperature moves upwards depending on the density difference. The high chimney located in the collector centre and creating a continuous vacuum effect draws in the rising system air and discharges it. During this time, the air passing over the turbine, which is located at a certain height inside the chimney and is one of the system elements, rotates and generates electricity through the generator. Other solar energy systems use a cycle to generate electricity by transferring the solar energy they receive to the working fluid. There is no such requirement for SCs, and electricity is generated directly from the solar energy passing directly to the system air via a turbine. In this case, a system that generates electricity directly from the sun can be defined for SCs. The system is privileged by being composed of only 3 structural elements and based on basic physical laws, which minimizes maintenance costs and technological infrastructure requirements. The schematic view of the system is given in Figure 1.
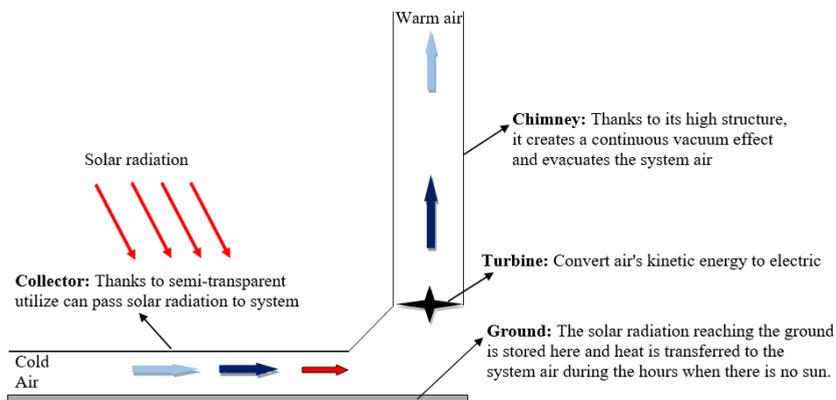

FIG. 1 : Solar chimney power plant scheme and system components.

The Manzanares pilot plant is of critical importance for SCs. After the first prototype, researchers intensively analyse the system and present numerous studies for system outputs and performance improvement. Although the performance critique of the system can be done with mathematical and theoretical studies, experimental studies are important. However, since many experimental setups will be needed for the sizing of system components, theoretical studies are important.

2.2 Experimental Studies for Solar Chimney Power Plants

The numerical analysis of solar energy systems is important. In particular, the inability to conduct experimental studies for all situations and climatic conditions may cause negativity. However, experimental studies are very important in determining system performance and creating models. In this section, the experimental prototypes established by the researchers for SCs and their details are given. The Manzanares pilot plant is the first and provides researchers with the opportunity for mathematical modelling as a large-scale system, thus contributing greatly to the development of the system. The overall efficiency of the system, which receives a high amount of solar energy due to the collector covering a large area, is well below 1%. Mullet (1987) claims that if the chimney height is 1000 m, the efficiency of the system will only reach 1% and criticizes it for low efficiency. The experimental prototypes established, and their technical details are given in Table 2. In experimental measurements, the hours at which the maximum air speed is taken may vary. Balijepalli et al., (2020) reported that the maximum air speed in the system was measured in the early hours with their experimental study, while in another experimental study, researchers claim that the maximum air speed was measured at 13 :00 (Al-Kayiem et al., 2019). Golzardi et al., (2021) measured the temperature difference and air flow speed in the system by changing the collector inlet height in the range of 0.05-0.20 m with a small-scale experimental prototype. They report that the maximum air speed of 0.33 m/s was obtained at a collector inlet height of 0.05 m and that increasing the collector inlet height reduced the speed. There are also researchers who measured the air speed in the system according to different chimney diameters. Mehla et al., (2011) showed with an experimental prototype that the decrease in the chimney diameter increased the air speed.

The biggest disadvantage of experimental studies is the difficulty in evaluating the different dimensional parameters. However, researchers present generalized approaches for some parameters. Kalash et al. (2013) create an experimental prototype using a sloped slope as a collector floor. Despite the maximum solar radiation of 600 W/m^2, they measure the air flow rate around 3 m/s with a small-scale system, which can be considered as a good performance in these dimensions. Atit (2009) takes experimental measurements by increasing the height of the system with a cylindrical 8 m high chimney. Then they measure the air flow rate in the divergent chimney design. They report that increasing the chimney height increases the air flow rate and the divergent chimney design has a positive effect on the air flow rate. Researchers evaluate the performance of SCs with different experimental prototypes, but the difficulty of changing the chimney size experimentally is the biggest obstacle to the studies. In this direction, it is normal for the studies related to the system to be theoretical and simulation oriented.

TAB. 2 : Experimental prototype examples for solar chimney power plants and technical details. *Collector area

Location	Collector Diameter (m)	Chimney Height (m)	Chimney Diameter (m)	Vmax (m/s)	Temp. Inc. (ΔT)	Collector Material	Ref.
Manzanares, Spain	122	194.6	5.08	15	20	Plastic and glass	(Haaf 1984)
Florida, USA	18.3	7.92	2.44	4	28	Plastic	(Pasumarthi and Sherif, 1998)
Hust, China	10	8	0.3	-	24.1	Fiberglass and Plastic	(Zhou 2007)
Thailand	8.2	8	2	-	-	Plastic	(Atit 2009)
Isparta, Turkey	16	15	1.2	4.5	23	Glass	(Üçgül and Koyun, 2010)
Hamirpur, India	1.4	0.8	0.08-0.12	0.5	5	Plastic	(Mehla et al.,2011)
Baghdad, Iraq	6	4	0.2	2.309	22	Plastic	(Ahmed and Chaichan, 2011)
Zanjan, Iran	10	12	0.25	4	27	Plastic	(Kasaeian et al., 2011)
Karak, Jordan	6.8	4	0.58	-	-	Plastic	(Al-Dabbas 2012)
Turkey	27	17.15	0.8	5.5	21-26	Glass	(Buğutekin 2012)
Texas, USA	11.58	4.88	0.19	2	-	Plastic	(Raney et al., 2012)
Botswana	-	22	2	4	7.5	Glass	(Zuo et al., 2012)
Kerman, Iran	1600*	60	3	11.4	22.7	Glass	(Najmi et al., 2012)
Damascus, Syria	-	9	0.31	2.9	19	Glass	(Kalash et al., 2013)
Japan	3	2	0.32	3	20-35	Acrylic Sheet	(Motoyama et al., 2014)
Tehran, Iran	3	2	0.2	1.3	26.3	Glass	(Ghalamchi et al., 2015)
Kompotades, Greece	-	25	2.5	5	-	Plastic	(Papageorgiou 2016)
Tehran, Iran	0.92	1.5	0.16	5.12	45	Glass	(Shahreza and Imani, 2015)
Japan	3	2	0.32	3	-	Acrylic Sheet	(Ohya et al.2016)
Kota, India	12	8	0.2	6	12.2	Polyethylene	(Lal et al., 2016)
Petronas, Malaysia	3	6.3	0.32	2.25	-	Perspex	(Al-Azawiey et al., 2017)
Edirne, Turkey	-	16.5	0.96	7	16-18	Policarbonate and glass	(Eryener at al., 2017)
Eqypt	6	6	0.15	-	-	Plastic	(Mekhail et al., 2017)
Sfax, Tunisia	2.75	3	0.32	1.32	13	Plastic	(Ayadi et al., 2018)
Sfax, Tunisia	3.7	2.95	0.16	2.2	18	Plastic Film	(Nasraoui et al., 2019)
Petronas, Malaysia	6	6.65	0.15	1.8	27	Perspex	(Al-Kayiem et al., 2019)
Erbil, Iraq	18	7.55	0.3	2.1	11.2	Glass	(Khidhir and Atrooshi, 2020)
Warangal, India	3.5	6	0.6	5.5	11.4	Glass	(Baljepalli et al.,2020)
Tafresh, Iran	2.25	1.94	0.1	0.33	23.6	Plastic	(Golzardi et al., 2021)
West Bengal, India	2.5	6	0.1	1.5	23	Plastic	(Mandal et al., 2022)

2.3   Theoretical and mathematical based studies

Experimental studies are indispensable arguments for performance analysis. However, it is not possible to study the effects of all parameters experimentally for SCs. Since there are many parameters affecting the system performance, it is impossible to examine the effects of all parameters experimentally. For this, theoretical and CFD studies gain importance. Theoretical studies are very important for establishing the mathematical infrastructure of the system. Table 3 presents a perspective from researchers who evaluate system performance with theoretical studies. System performance directly depends on climatic parameters and system design. The effect of climatic parameters such as ambient temperature and solar radiation on system performance is carried out by researchers many times with both experimental and non-experimental studies (Cuce et al., 2022b). System design is related to the size and design of the structural elements. Since increasing the collector size will increase the amount of energy entering the system, it is expected to provide a direct performance increase (Cuce et al., 2023a). The chimney is the driving force of the system and is in the centre of the collector and constantly forces the system air, whose temperature increases under the collector, to move upwards (Cuce et al., 2021a). Although SCs is a solar energy system, it does not provide power output by using only solar energy. If the chimney in the system structure is built at a sufficient height, it can provide power output during the hours when there is no sun by creating a continuous pressure difference. As the physical density of the air decreases, it moves upwards due to buoyancy effects. Since SCs has a high chimney due to its structure, it creates a pressure difference depending on the height difference at the chimney inlet and outlet. The pressure difference, which is the driving force of the system, can be given with the following equation depending on the chimney height and the density of the air (Schlaich, 1995) :

$$\Delta P_{tot} = g \int_{0}^{H_{ch}} (\rho_a - \rho_{ch})\,dz \qquad (1)$$

In the equation, ΔP_{tot} represents the total pressure difference in the system, g represents the gravitational acceleration, H represents the height, represents the density, a represents the initial condition and ch represents the chimney. As can be understood from the equation, the increase in the chimney height will increase the pressure difference of the system. With a different equation, the researchers present the pressure difference as follows (Koonsrisuk et al., 2010) :

$$\Delta P_{tot} = g\beta\rho H_{ch}\Delta T \qquad (2)$$

In the equation, β represents the volumetric thermal expansion coefficient, and T represents the temperature difference between the inside of the chimney and the ambient air at the same height. As can be understood from this equation, the chimney height is quite critical for the potential of the system. The system efficiency is a function of the collector, chimney, and turbine efficiency. Naturally, chimney efficiency is

important. The following equation is presented in the literature for chimney efficiency (Schlaich, 1995) :

$$\eta_{ch} = \frac{gH_{ch}}{c_p T_a} \tag{3}$$

Here, c_p represents specific heat, T_a represents ambient temperature, and n represents efficiency. In the equation, it is seen that the increase in the chimney height will directly increase the chimney efficiency and that there is a linear relationship. Whether continuously increasing the chimney height will continuously increase the system performance is discussed in detail by researchers. Although increasing the chimney height increases the system performance, some researchers argue that there are limitations to this situation. The studies that take the Manzanares pilot plant as a reference and the power output data of the chimney height, keeping other dimensional parameters constant, are given in Figure 2 in comparison. Although the chimney height increases the power output, it is debatable whether this is continuous. Zhou et al. (2009), who evaluated the effect of increasing only the chimney height on the system performance by fixing the dimensions of the Manzanares pilot plant with a theoretical model, claim that continuous power increase is not possible and even that there will be a decrease after a certain point. They show that the maximum power output will be obtained at a chimney height of 615 m for the system and this value will be 102.2 kW. Although this view is controversial, it seems that researchers will continue to work on the subject. There are also researchers who present the electrical power (P_{elec}) to be obtained from the system with a mathematical model as follows (Larbi et al., 2010) :

$$P_{elec} = \frac{2}{3}\left(\eta \frac{gH_{ch}}{c_p T_a}\right) A_{coll} G \tag{4}$$

In the equation, A_{coll} represents the collector area and G represents solar radiation. If you pay attention, you will see that the expression for chimney efficiency given in Equation 3 is the same here. It is clearly seen in Equation 4 that the power output is directly dependent on the chimney height. In this case, it is natural to comment that there will be a continuous power increase. Researchers show that for a system with a chimney height of 200 m and a collector diameter of 500 m, the increase in chimney height will continuously increase the power output (Larbi et al., 2010). Another researcher, who evaluated the effect of chimney height on system performance with a mathematical thermal model, emphasizes that increasing the chimney height of a system with a collector diameter of 2000 m from 400 m to 1000 m will increase the power output by 3 times (Hamdan 2013). They also claim that the discretized chimney model they present gives healthier results than the simple chimney model. Larbi et al., (2015) analyse the effect of stack height and energy storage on the ground by using a mathematical model, taking the Manzanares pilot plant measurements as reference. In their study, they show that creating a water base on the ground for energy storage reduces the maximum power output but increases the total daily energy production. They report that 100 kW power output is obtained with the energy storage unit on

the ground at noon in July, and if the stack height is increased to 300 m, the power output will increase by 60% to 175 kW. Ngala et al., (2015) present a mathematical study to analyse the SCs performance parameters and present the performance of a system with a collector diameter of 700 m and a stack diameter of 10 m at 800 W/m^2 constant solar radiation and an ambient temperature of 35°C. The researchers present power output data for a stack height of 0-700 m and claim that the power output increases linearly with the stack height and will exceed 3500 MW. They present the pressure difference (P) between the chimney inlet and the surrounding environment with the following equation :

$$\Delta P = \rho_{air} g H_{ch} \frac{\Delta T}{T_a} \tag{5}$$

As can be understood from the equation, the increase in the stack height directly increases the pressure difference, which is positive for the system performance. Khelifi et al., (2016) evaluate the effects of climatic and geometric parameters on the system performance with a mathematical model. They present the effect of the increase in the stack height on the power output for the system with a collector diameter of 600 m at 1000 W/m^2 solar radiation and 298 K ambient temperature. They claim that the system will give a power output of 1.84 MW with a stack height of 200 m, while it will give a power output of 4.6 MW with a stack height of 500 m. They argue that the increase in the stack height will increase the power output linearly. Choi et al., (2016) design a large-scale system with a collector radius of 3000 m and a stack diameter of 100 m and present a performance analysis with mathematical solution. In addition to the effect of geometric parameters in the analysis, they also discuss the addition of energy storage with water. They evaluate the stack height in the range of 0-2000 m at 1000 W/m^2 constant solar radiation and 20°C ambient temperature. They claim that the power output will increase exponentially with increasing stack height. They show that the power output, which is approximately 100 MW at a stack height of 1000 m, will be approximately 290 MW at a stack height of 2000 m. Mathematical based analyses, while being practical, may not provide detailed data for the system. It is quite difficult to obtain detailed data such as temperature, air flow rate, and pressure difference within the system. Computational fluid dynamics (CFD) offers richness where all components of the system can be evaluated together and the dynamics within the system can be better observed. It is especially important for evaluating parametric effects. When evaluating climatic parameters, the increase in solar radiation not only increases the amount of energy entering the system but also affects the change in air temperature along the collector, so the use of CFD in analyses is important. It is seen that researchers present the effects of temperature and solar radiation in detail with CFD studies (Cuce et al., 2020a). Similarly, geometric parameters and different designs are also investigated in detail with the CFD method (Cuce et al., 2020b ; Cuce et al., 2021b). Criticism regarding the studies conducted with the CFD method for SCs performance is presented in another title.

Article title	System details	Findings	Ref.
Up-Draught Solar Chimney and Down-Draught Energy Tower – A Comparison	It is desired to evaluate the electrical power of SCs with a developed mathematical model. The mathematical model, which is verified with the data from the Manzanares pilot plant, calculates the electrical power of a large-scale system with a chimney height of 1000 m and a collector diameter of 4000 m at different solar radiations.	They claim that an increase in solar radiation will increase the electrical power available from the system, but that increasing the initial temperature will have the opposite effect. They show that at 1000 W/m² solar radiation, a large-scale system will produce 100 MW of electricity.	Weinrebe and Schiel, (2001)
Thermal and technical analyses of solar chimneys	They develop a mathematical model to analyse the performance of SCs and conduct a potential power study for a large-scale commercial model. They interpret the effect of changes in structural parameters of a system with a 1000 m stack height on the outputs.	They show that the performance results obtained with the mathematical model are in good agreement with the data from the Manzanares pilot plant. They argue that increasing the stack height and increasing the collector size will directly increase the power output. They claim that the system will give maximum performance since the turbine pressure drop is 0.97.	Bernardes et al., (2003)
Case study of solar chimney power plants in Northwestern regions of China	They developed a mathematical model to predict the performance of a system that could be installed in three different rural areas in China. The system they designed has a stack height of 200 m and a collector diameter of 500 m.	They claim that with the system to be installed; an average monthly power output of 110-190 kW can be produced throughout the year. They also show that while the power output increases with increasing solar radiation, it decreases with the ambient temperature. They also argue that the chimney height and collector size will have a positive effect on the system.	Dai et al., (2003)
Solar chimney power plants for high latitudes	They predict with a mathematical model for a possible system to be established for 3 different regions of Canada in high latitudes. They solve the mathematical code they created through MATLAB and present an evaluation at different angles for the collector placed on a sloped ground.	They argue that although the energy obtained from the sun will decrease in plants to be built at high latitudes compared to horizontal collectors, this situation will be compensated by the abundance of land. They also show that the chimney height will be reduced by 90% with the increase in collector size. They claim that the efficiency of the whole system will reach 0.79%.	Bilgen and Rheault, (2005)
Solar chimney power plant performance	A mathematical model is developed for the performance analysis of a large-scale system with a stack height of 1000 m. In the detailed model, where all losses are considered, a 24-hour power output calculation is presented for the dates 21 June and 21 December.	They report that the system will provide continuous power output for 24 hours and that power output will exceed 120 MW on December 21. They claim that the power output will be lower on June 21 and that the power output is a function of the collector shape and collector inlet height.	Pretorius and Kröger, (2006)

Analysis and feasibility of implementing solar chimney power plants in the Mediterranean region	They make performance and cost analysis for a large-scale power plant that can be established in the Mediterranean region. They present daily and annual output estimates for a system with a 550 m chimney height and 1250 m collector diameter with their theoretical calculations.	They state that the system will provide different performances according to the changing climatic conditions in different regions. They claim that daily production can reach 40.811 kWh and that the cost of electricity production will fall below 0.3 €/kWh for a period of nearly 40 years with the assumption of 6% annual interest.	Nizetic et al., (2008)
Cost analysis of solar chimney power plants	A detailed cost analysis is presented based on a reference plant. The analysis also includes the impact of carbon credits on the balanced electricity cost. Three plants with equal capacity of 100 MW but different geometric configurations are analysed. The reference plant has a stack height of 1000 m and a collector diameter of 4300 m.	It is claimed that previous cost studies in the analysis where all the structural elements were included in the calculation in detail were quite optimistic. It is presented in the study that the annual electricity production will be less than presented and its cost will be 1-2 times more than estimated.	Fluri et al., (2009)
Performance of solar chimney power plant in Qinghai-Tibet Plateau	They analyse the performance prediction of SCs to be installed on the Qinghai-Tibet Plateau by creating a simple mathematical model. Possible outputs of a plant with a stack height of 1000 m and a collector diameter of 5650 m for the climatic conditions of 10 different regions are presented in different regions.	They report that while increasing solar radiation increases power output, ambient temperature has the opposite effect. They predict that 20-105 TJ of power can be produced with systems that increase power output with increased chimney height and collector height. They report that this production will be more than 10% of the total production in China.	Zhou et al., (2010)
Performance evaluation of solar chimney power plants in Iran	They develop a mathematical model to analyse the performance of SCs and predict the performance of potential power plants to be installed in Iran. They evaluate the monthly average solar radiation and temperature data of this system with a chimney height of 350 m and a collector diameter of 1000 m according to the climate conditions in different regions.	They report that system performance increases with increasing solar radiation, but performance will decrease with ambient temperature. In the study where annual graphs are presented, it is claimed that there will be a power production of close to 170 kW in the summer months and that an annual power production of 1-2 MW is possible.	Sangi (2012)
Performance study of solar chimney power plant System with a sloped collector	They perform geometric analysis and performance prediction for SCs that are likely to be installed on steep slopes. They present performance data for systems with different stack heights, collector sizes, and stack diameters. They compare power output for different collector slopes.	In the reference case, the horizontal collector provides maximum power output in summer. However, when looking at the annual total electricity production, it is seen that the 45° collector slope gives the best performance. It is expected that the increase in the collector area will increase the system efficiency and power output.	Li et al., (2013)

Tracking consideration of tilted collector solar updraft tower power plant under Malaysia climate conditions	They develop a mathematical model for SCs performance and solve it in MATLAB. After verifying the study based on the Manzanares pilot plant, they evaluate the effect of collector tilt on system performance for Malaysian climate conditions.	They claim that in Malaysian conditions, 10* collector inclination will give better performance than other inclination angles. They claim that in the reference case; the inclined collector will increase the power output by more than 3.5 kW compared to the horizontal collector. They state that the maximum efficiencies with the inclined collector will be 51% for the collector and 0.165% for the system.	Gitan et al., (2015)
Novel concept of enhancing the performance of sloped solar collector by using natural anabatic winds	They perform a performance analysis of a system with a collector placed on a slope with a mathematical model. They present the power output; temperature rise under the collector and efficiency values of the system with a collector area of 950.000 m² on a slope of 38.4° with a chimney height of 123 m.	They claim that the new system performs better than systems with traditional inclined collectors. They report that by increasing the collector area up to 5 times on the mountainside, the system efficiency will increase by 183% and the electricity cost will decrease by 64.7%.	Zhou et al., (2016)
Thermodynamic analysis of a solar chimney power plant system with soil heat storage	They conducted a study that they found to be sufficient at a depth of 4 m by creating a 1D mathematically based theoretical model based on the geometry of the Manzanares pilot plant. After presenting 24-hour power output, temperature rise, and air flow rate graphs, they presented system performance critiques for 3 different soil materials.	They report that the data obtained with the theoretical model is consistent with the experimental data and that a constant temperature will be measured for 24 hours at a depth of 1 m. After showing that the energy storage unit in the ground will significantly reduce the fluctuation in power output, they include the effect of different thermal capacity and heat transfer coefficient on daily total power production.	Guo et al, (2016)
Comprehensive mathematical study on solar chimney powerplant	They try to analyse the performance of SCs by creating a comprehensive mathematical model. They present performance data for collector and chimney at different angle values in the results they get through MATLAB. They present power output and temperature difference values based on different angle values over mass flow rate and turbine pressure drop.	They claim that under the same conditions, when the collector inlet height is lower than the outlet height, α>0, and β<0 can be obtained from a divergent stack design where the stack inlet diameter is smaller than the outlet diameter. They state that the optimum turbine pressure drop should be 70-85% of the total pressure difference. They show that with only stack and collector inclination angles, the maximum power output can reach 380 kW.	Setareh (2021)
Modelling the thermal performance for different types of solar chimney power plants	They estimate the power output for a power plant with the dimensions of the Manzanares pilot plant for 5 different regions in Iran using a mathematical model. Data is presented for comparison by comparing the ambient temperature and average solar radiation for the regions.	They report that in general the maximum power output is similar across regions, but the total annual production will vary significantly. They argue that the power plant to be built in Shiraz will produce 92% more power output in September than the Manzanares pilot plant data. They also report that Shiraz will produce an average of 7.14% more than the other four cities.	Smaisim et al., (2022)

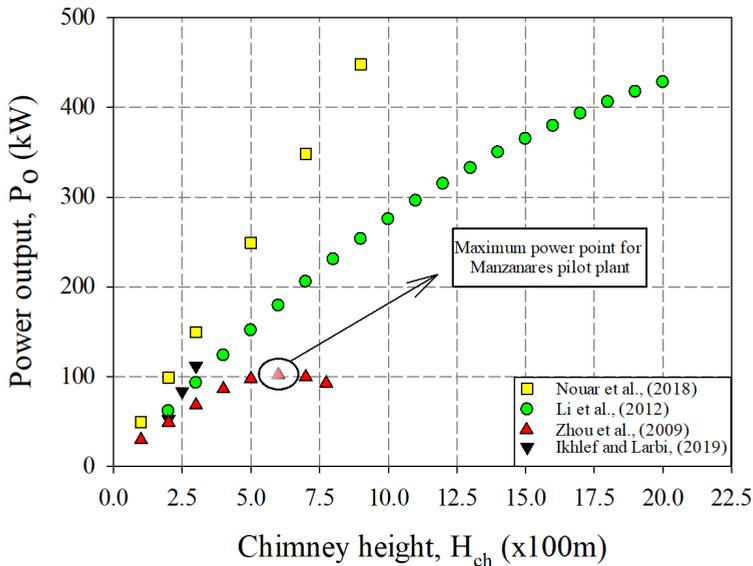|		
Study on refined mathematical model of solar chimney power plant integrated with seawater desalination and the influence of dewing	They develop a mathematical model based on heat transfer based on a small-scale experimental prototype and solve it in MATLAB. They present the results of the data obtained from the experimental and mathematical model throughout the day on temperature and solar radiation, as well as the amount of water obtained from the system by condensation.	They show that the data obtained with the mathematical model differs from the experimental data with an error of less than 10%. They claim that the critical relative humidity for condensation to occur with changing climatic conditions is 51% and that efficiency will decrease with an increase in relative humidity. Zuo et al., (2023)
Enhancing the electricity and desalinated water production from solar chimney power plants through integration with nuclear power plants: A case study in Jordan	They present an evaluation on the potential increase of pure water production from seawater by integrating waste heat of a nuclear power plant into the system by developing a mathematical model. They make an impression of the possible power output in the Jordan region by placing a seawater pool on the stack floor of a system with 200 m stack height and 250 m collector diameter.	In the reference case, while a monthly average of 9.44 kilo tons of water and 25.73 kWh of electricity production is foreseen, they claim that with the integrated system this will be 63.81 MWh with 22.96 kilo tons of water. They report that the system will reach its maximum level with 69.4 MWh in December. Almomani et al., (2024)

Fig. 2 : Comparison graph of researchers analysing the effect of chimney height on Manzanares pilot plant performance with mathematical models.

2.4   Computational Fluid Dynamics (CFD) based studies

Solar energy has an important place among renewable energy sources, and besides having infinite potential, it can be used in wide geographies. Evaluating the performance of solar energy systems is as important as their design. For this purpose, the fact that it is not possible to obtain data about all situations experimentally and especially the fact that it is not possible to establish different mechanisms for geometrically large-scale systems pushes researchers to theoretical and CFD studies. Theoretical studies are mathematically based and are generally prepared in the light of experimental data based on thermodynamic and heat transfer equations. The biggest advantage of CFD studies is that they allow the analysis of the system in every aspect. There are different CFD programs that work on the principle of solving conservation equations simultaneously via a computer. SCs performance is simulated by researchers using different software. While Chao et al. (2018) performed the annual performance analysis of a large-scale system via TRNSYS, Romeo et al. (2017) performed the thermodynamic relations and system performance within SCs with OPEN-FOAM simulation. Although different software is available, ANSYS FLUENT CFD software is quite successful for air flow, temperature, pressure, and velocity analysis within the system (Cuce et al., 2022b). Table 4 includes the study details and critical findings of the researchers who performed the SCs analysis with the CFD method.

Article title	System details	Findings	Ref.
Numerical and analytical calculations of the temperature and flow field in the upwind power plant	In their CFD study based on the Manzanares pilot plant measurements, they evaluate the system outputs with the k-ε standard k-ε turbulence model.	They show that increasing solar radiation will increase the temperature, pressure difference, and air flow velocity across the collector. They also report that the ground temperature will increase with increasing solar radiation. They claim that the air flow velocity at the collector outlet will approach 9 m/s.	Pastohr et al., (2004)
Analytical and numerical investigation of the solar chimney power plant systems	They analyse the performance of the Manzanares pilot plant with a 3D CFD model at 20°C ambient temperature and 800 W/m² solar radiation. They present performance data for different solar radiation and chimney heights.	They state that the increase in chimney height will increase the air flow rate and power output and will also support the driving force of the system. They claim that at 1000 W/m² solar radiation, the system efficiency will be 1% for a chimney height of 300 m and 3% for 1000 m.	Tingzhen et al., (2006)
Numerical analysis of flow and heat transfer characteristics in solar chimney power plants with energy storage layer	In their study based on the geometry of the Manzanares pilot plant, they perform a performance analysis of a system with an energy storage unit. They evaluate the effect of using soil and gravel as ground material at 200-800 W/m² solar radiation range and 20°C air temperature on the temperature, pressure and air velocity distribution in the system.	They state that the ground temperature at maximum solar radiation is a maximum of 75°C and that this differs from experimental data. They state that the energy storage rate of the energy storage layer increases with increasing solar radiation. They also emphasize that the maximum air speed within the system is 11 m/s.	Ming et al., (2008)
Simulation of flow and heat transfer in 3D solar chimney power plants numerical analysis	After validating the model, they created with the 3D and 5° CFD model with the Manzanares pilot plant, they revised it to predict performance for systems of different sizes for an ambient temperature of 300 K. The collector radii of two separate systems with stack heights of 100 and 400 m are 60 and 240 m.	They claim that the results of the 5° CFD model are quite consistent with similar studies in the literature, and that the model with a higher chimney height has higher efficiency, while the maximum power output will be obtained with the model with a large collector.	Kalantar and Zare, (2011)
Evaluation of the influence of soil thermal inertia on the performance of a solar chimney power plant	They use the ANSYS-FLUENT code to interpret the effect of soil thermal inertia, using the Manzanares pilot plant geometry as a reference. They present data on air flow velocity at the stack inlet, soil temperature at the ground, and pressure difference throughout the day.	They state that the system will give up to 10% more power output than the reference case with compacted soil and that the air velocity in the system will be approximately 9 m/s at the chimney inlet. They show that the mass flow rate will decrease by approximately 50% when the turbine is not active.	Hurtado et al., (2012)

Title	Description	Findings	Reference
Solar Chimney Power Plant Performance Analysis in the Central Regions of Iran	After creating a 2D axisymmetric CFD model based on the Manzanares pilot plant dimensions, they perform a 12-month performance evaluation for the city of Kerman. They present a 12-month power output graph for different turbine efficiencies as well as a comparison of the temperature distribution across the collector for different months.	They report that the turbine efficiency will increase the power output and that the maximum power output will be achieved in the summer months. They claim that with a turbine efficiency of 0.95, there will be 48MWh of electricity production in the 8th month. They estimate that there will be a temperature increase of approximately 20°C along the collector.	Asnaghi et al., (2013)
Numerical Simulation and Comparison of Conventional and Sloped Solar Chimney Power Plants: The Case for Lanzhou	They present a performance comparison between conventional solar chimney power plants and solar chimney power plants to be installed on sloping ground using a 2D CFD study. After demonstrating the performance of conventional systems using the Manzanares pilot plant as a reference, they evaluate the annual power generation of a sloping system to be installed in Lanzhou.	They report that they obtained a maximum air velocity of 14.33 m/s and a temperature increase of 21.5 K under the collector in CFD results at 1000 W/m² solar radiation. They show that the system to be installed on sloping ground provides more balanced power production and is more efficient than the traditional system, and that the height of the chimney and collector is important for effective pressure.	Cao et al., (2013)
Study of the influence of geometric parameters on a solar chimney power system	With the 3D CFD model, they analyse the mass flow rate and air flow velocity at the chimney outlet of the Manzanares pilot plant depending on the chimney height at 800 W/m2 solar radiation and 293 K ambient temperature. Similarly, they include performance data regarding collector size and collector height.	They claim that the mass flow rate, which is 850 kg/s at a chimney height of 100 m, will exceed 1200 kg/s at a chimney height of 300 m. Similarly, they claim that the temperature increase under the collector will increase from 20 K to 23.5 K. They state that the increase in collector size will have a positive effect on both the air flow rate and the temperature increase under the collector.	Dhahri et al., (2013)
Numerical study on the performance of a solar chimney power plant	A 3D CFD study including radiation model, solar load, and real turbine model evaluates the performance of SCs. It provides a perspective on system performance through turbine pressure drop based on the Manzanares pilot plant measurements. The analyses are performed for 0-1000 W/m² solar radiation at 302 K ambient temperature.	The radiation model has a significant effect on system performance and should be enabled in the analysis. Turbine rotation speed and solar radiation have a positive effect on the system power output, but after a certain point, an increase in turbine rotation speed becomes a negative effect. For 150 rpm and 800 W/m², the power output is approximately 59 kW. Also, the power output, which is 55.5 kW for 0-degree zenith angle, decreases to 46 for 30 degrees.	Guo et al., (2015)

3D numerical study of flow in a solar chimney power plant system	They present data on temperature, static pressure, and air velocity across the collector for the Manzanares pilot plant with a 3D CFD model. They perform the analyses for 200, 600, and 1000 W/m² solar radiation at an ambient temperature of 293 K.	They show that the maximum static pressure is -130 Pa and that lower static pressure can be obtained with solar radiation. They report a maximum air speed of 14.61 m/s and a temperature increase under the collector of 24.07 K and claim that the results are consistent with experimental data.	Tayebi et al., (2015)
Numerical-Analytical Assessment on Solar Chimney Power Plant	They perform the performance analysis of the Manzanares pilot plant by applying a heat flux of 300-1000 W/m² on the collector floor with a 2D CFD model. They also compare the CFD results with the analytical model results they created. They use the turbine kinetic energy of 0.5mu² in the power output calculation (m is mass flow rate and u is velocity).	They show that the maximum air flow velocity is 18.8 m/s and the air flow velocity increases with increasing solar radiation. They report that the analytical-CFD model is more consistent with the experimental data according to the CFD results and report a power output of approximately 40 kW for 1000 W/m² solar radiation.	Fathi et al., (2016)
CFD (computational fluid dynamics) analysis of a solar-chimney power plant with inclined collector roof	They evaluate the effect of the inclined collector on the system performance by keeping the collector inlet height constant and increasing the collector outlet height at 300 K ambient temperature with a 3D CFD model using the Manzanares pilot plant measurements as reference. They present the velocity and temperature distribution in the system in the simulations they make by applying 850 W/m² radiation on the collector. They compare the collector efficiency, mass flow rate, and power output for different collector outlet heights.	After reporting that the model yields result that are quite consistent with the pilot plant experimental data, they emphasize that increasing the collector outlet height has a positive effect on system performance. They show that the maximum air velocity is 9.1 m/s with the horizontal collector in the reference case, and that if the collector outlet height is increased to 5 m, the maximum velocity will increase to 9.7 m/s. They claim that the power output also increases from 51 kW to 56.6 kW. They suggest that similar effects will be seen in the mass flow rate and collector efficiency.	Gholamalizadeh and Kim, (2016)
Numerical Modelling of the Compressible Airflow in a Solar-Waste-Heat Chimney Power Plant	They present the performance analysis of a waste heat integrated solar chimney power plant assuming air as an ideal gas. The study, which is based on the Manzanares pilot plant with a 3D CFD model, includes system outputs with flue gas injection from 4 different points at the chimney inlet.	After presenting that the results obtained from the created model are consistent with the experimental data, the density change for different flue gas percentages along the chimney is presented in detail. They show that under the same conditions, the system that gives a power output of 49 kW in the reference case will give a power output of 94 kW with 200% flue gas.	Hu and Leung, (2017)

A parametric simulation of solar chimney power plant	After creating and validating a 3D CFD model based on the dimensions of the Manzanares pilot plant, systems with different geometries were created. They provide outputs such as temperature, air velocity, and power output at 600, 800, and 1000 W/m² solar radiation at 299.5 K ambient temperature.	They present simulation results showing that at 1000 W/m2 solar radiation, the maximum air flow velocity inside the pilot plant is 15.7 m/s and the temperature increase under the collector is 21.9 K. They reiterate that solar radiation increases system performance and emphasize once again that sizing is important for power output.	Hooi and Thangavelu, (2018)
Numerical investigation of solar chimney power plants performance for Saudi Arabia weather conditions	They estimate the performance of a potential system in Arabia at 6 different locations using the Manzanares pilot plant measurements in a 3D CFD model. They present a 12-month power output and collector efficiency comparison using the RNG k-e turbulence model and the discrete ordinates (DO) model for solar radiation.	They claim that Riyadh city will have an average monthly power production of 56 kW throughout the year, while Bisha region will be the best location for installation with an average annual power production of 63 kW. They report that system performance is affected by both solar radiation and temperature, and that collector efficiency varies between 10-29% throughout the year.	Abdelmohimen and Algarni, (2018)
Effects of novel collector roof on solar chimney power plant performance	They evaluate the effect of different geometry roughness placed on the collector on the performance of the Manzanares pilot plant with a 3D CFD model. They include the effect of triangular, narrow corrugated, and square roughness at different sizes and repetitions at 300-1000 W/m² solar radiation.	They report that at 1000 W/m2 solar irradiance, the power outputs of the triangular, curved, and square-groove designs are increased by 169%, 96%, and 19%, respectively, over the smooth case. They also claim that the triangular-groove and curved-groove designs have a 42% and 26% increase in Nusselt number over the smooth case.	Elwekeel et al., (2019)
Numerical investigation on the performance of a small scale solar chimney power plant for different geometrical parameters	They design a small-scale system with a height of 3 m and a collector diameter of 3 m and conduct a CFD study. They present comparative system outputs for different collector sizes and chimney designs. They also include the effect of divergent chimney design on system performance.	The following footnotes are extracted from the study: There is an optimum situation for collector height and slope, chimney height increases system performance but there is no linear increase, divergent chimney gives better performance.	Yapıcı et al., (2020)
Impacts of ground slope on main performance figures of solar chimney power plants: a comprehensive CFD research with experimental validation	In the 3D CFD model, the Manzanares pilot plant is taken as a reference and the effect of the ground slope on the system performance is analysed in detail. The change in the system outputs is monitored by giving the ground slope from 5 m inside the chimney entrance to the chimney exit.	They show that the power output increases with increasing ground slope but there is a tendency to converge. They claim that the system, which gives a power output of 54.3 kW in the reference case, provides a 17% increase in power output at approximately 64 kW at 0.5° ground slope.	Cuce et al., (2021b)

Performance evaluation of solar chimney power plants with Bayburt stone and basalt on the ground as natural energy storage material	The effect of using Bayburt stone and basalt as ground material on system performance is evaluated with the 3D CFD study, taking the Manzanares pilot plant as reference. Performance outputs are presented for different solar radiation and ambient temperature.	They emphasize that solar radiation increases system performance through the model they validate with experimental data. They claim that 41 kW power output will be obtained from the system at 800 W/m2 solar radiation and 300 K ambient temperature, while they claim that the use of economical materials on the ground does not have a negative effect on system performance.	Cuce et al., (2022c)
Reliable renewable power production by modelling of geothermal assisted solar chimney power plant	In their CFD study based on the Manzanares pilot plant geometry, they analyse the improvement in system performance by integrating geothermal hot water with a temperature of 75°C into the system ground. The effect of the spring water coming to the system ground with a flow rate of 40 Liters/second on the system at 200-900 W/m^2 solar radiation is reported.	They show that the air flow velocity in the system, which is approximately 15 m/s in the reference case in summer, will increase to 16 m/s with the addition of geothermal resources. They claim that the annual production will increase from 263946 kWh to 319537 kWh with the addition of geothermal resources. They argue that the unit cost of electricity will decrease with the addition of geothermal resources.	Noorollahi et al., (2023)
Performance Approach to Solar Chimney Power Plants: Chimney and Collector Effect	In the 3D CFD study, the model, which takes the Manzanares pilot plant dimensions as reference, evaluates the effect of the stack height and collector radius on the power output.	They report that increasing the stack height and collector radius increases system performance, but after a certain point the effect diminishes.	Sen et al., (2024)
Performance analysis of solar chimney power plant with waste heat integration on the ground	Analysis of system performance by integrating waste heat of a gas power plant into a solar chimney power plant is done with a 3D CFD model by taking the geometry of the Manzanares pilot plant. System performance is evaluated at 816.9 K waste heat temperature, 294 K ambient temperature and 400 W/m^2 solar radiation.	They show that even during the hours when there is no sun, the system will provide a power output of over 14 kW with the waste heat integration. They claim that the power output of the system, which is 20.68 kW at the reference temperature and solar radiation, will increase by 63.47% to 33.8 kW with the waste heat integration.	Cuce et al., (2025)

When CFD studies are examined, it is seen that the system can be considered compared to theoretical studies and especially hybrid studies are analysed better (Cuce et al., 2022b). It is clearly seen in the studies in the literature that increasing the chimney height has a positive effect on system performance. Since the chimney is the driving force of the system, this is a normal expectation. Cuce et al., (2020c) provide a detailed analysis of the effect of changing the chimney height in the range of 100-500 m on system performance based on the Manzanares pilot plant measurements. They show that the increase in chimney height increases system performance in their simulations at 20°C ambient temperature and 1000 W/m^2 solar radiation. The data for the maximum air flow rate and power output in the system for different chimney heights in the study are presented in Figure 3.
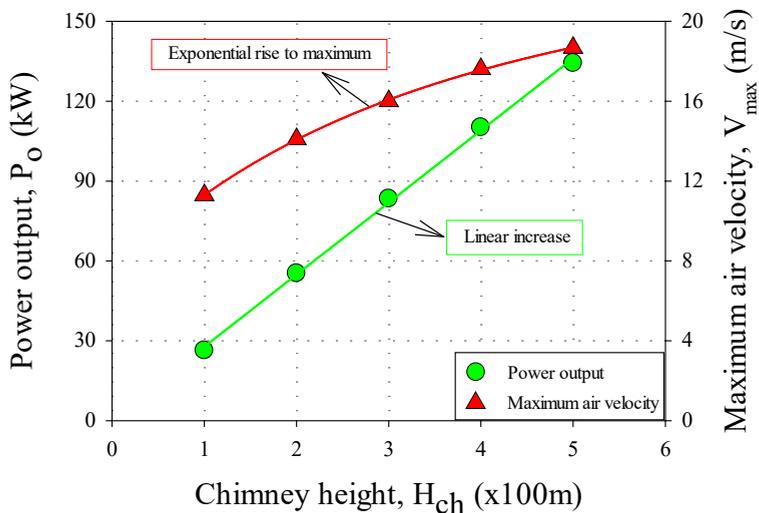

FIG. 3 : Graph of maximum air velocity and power output in the system at different chimney heights for the Manzanares pilot plant (Cuce et al., 2020c).

It is understood from the graph that although the chimney height increases the power output linearly, the same situation is not valid for the air speed. The positive effect of the chimney height on the system performance is generally accepted in the literature. However, there are some differences among the researchers. While some researchers predict a linear increase as in Figure 3, some researchers argue that there is a limitation for the increase in the chimney height (Karimipour-Fard, and Beheshti, 2017). The comparative graph of the chimney height on the power output of the previous studies conducted by the researchers based on CFD for the Manzanares pilot plant is given in Figure 4.
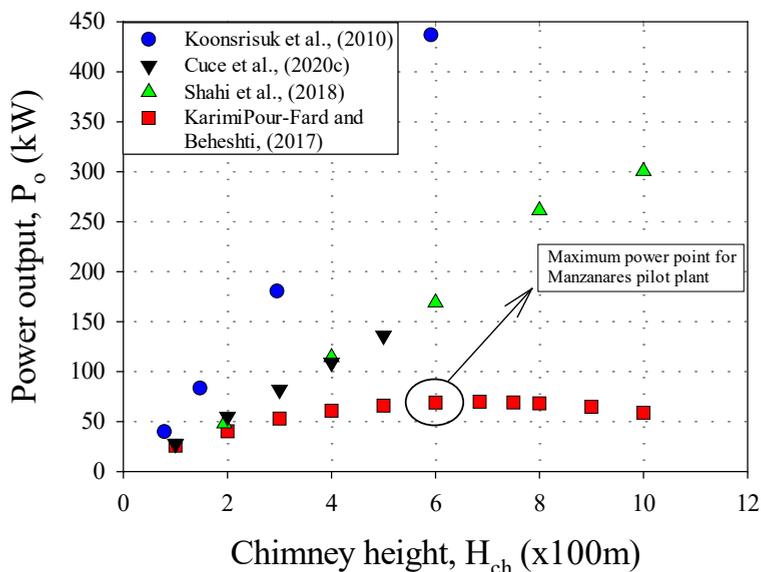
Fig. 4 : Comparison graph of researchers analysing the effect of chimney height on Manzanares pilot plant performance with CFD models.

For the chimney, not only the height change but also the diameter change has great effects on the system performance. Since the chimney provides the discharge of system air, it is important to interpret the effects of the diameter change. A large chimney diameter can increase the mass flow rate by allowing more air to be discharged from the system. Although this situation seems positive for the power output, it can have a negative effect on the maximum air speed by reducing the temperature increase of the air under the collector. Similarly, a small chimney diameter can reduce the amount of air discharged from the system and increase the temperature increase of the air under the collector. In this case, the decreasing flow rate negatively affects the system performance. Considering all these reasons, it is inevitable to have an optimum diameter value for the chimney diameter. Karimi-Pour-Fard and Beheshti (2017) claim that the chimney radius where the maximum power output is obtained for the Manzanares pilot plant is 6-6.5 m with their CFD study. Gholamalizadeh and Mansouri (2013) stated in their analysis for the Kerman prototype that increasing the chimney diameter from 3 m to 5 m would increase the mass flow rate by 150%. It is controversial that the same increase is seen in the power output. Toghraie et al. (2018) presented a detailed analysis of the effect of system parameters on the outputs with a CFD model with a chimney height of 100 m and a collector diameter of 200 m. They took the collector height as 2 m and changed the chimney radius in the range of 1-10 m. They showed in the study that there is a radius value at which the system gives maximum power output. Ikhlef and Larbi (2019) showed with a mathematical model that increasing the chimney diameter for the Manzanares pilot plant increased the system performance by up to 100%. This situation necessitates detailed analysis for the chimney diameter. In Figure 5, Cuce et al. (2021c) present the change in the

power output of the system by changing the chimney diameter of the Manzanares pilot plant in the range of 4.86-64.86 m with the CFD study.
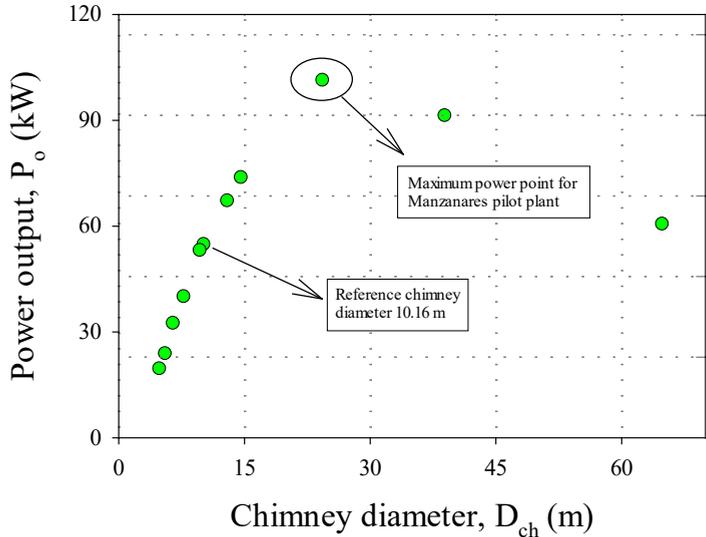
FIG. 5 : Manzanares pilot plant power output graph for different chimney diameters (Cuce et al., 2021c)

It is clear in the literature that the chimney height and diameter have serious effects on system performance. Chimney design is also important with these dimensional effects. The inlet and outlet diameters of the cylindrical chimney used for the pilot plant are fixed. It is seen that some researchers analyse the system by bringing special approaches to chimney design. It is seen that researchers make performance analysis with the convergent and divergent chimney concept by changing the chimney inlet and outlet diameters. In the analyses made on the area ratio (AR) by proportioning the chimney outlet area to the chimney inlet area, it is observed that the system performance changes seriously. Some researchers evaluate the divergent chimney angle by ensuring that the chimney positioned vertically from the chimney inlet deviates by a certain angle. Table 5 presents the study details and findings of the researchers who evaluated chimney design in the literature. The expression given in the table represents the chimney divergence angle and AR represents the ratio of the chimney outlet area to the chimney inlet area.

Table 5. Details of studies on chimney design using the Manzanares pilot plant as reference and literature examples of their findings.

Reference	Cylindrical results V_{max} (m/s)	Power output (kW)	θ or AR
Hu et al., (2017)	They analyse the system performance based on the ratio of the chimney outlet area to the chimney inlet area (AR) with a 3D CFD model. They evaluate the performance data in the range of 1-32 AR in solutions performed at 302 K ambient temperature.	They claim that the system, which gives a power output of 50.37 kW with a cylindrical chimney in the reference case, can reach 680 kW by increasing the chimney outlet area.	10
Xu and Zhou, (2018)	The effect of divergent chimney design on system performance is investigated with 3D CFD analysis. They include the effect of the divergent chimney angle on the power output of 0-12.2° (1-24.2 for AR) with 250 W/m² heat flux applied on the ground at a constant ambient temperature of 23.5°C.	They claim that the divergent stack design increases system performance, increasing the power output from 19.5 kW at the reference case to 231.7 kW at 8.7 AR. They show that higher AR values will start to reduce the power output.	8.7
Hassan et al., (2018)	They evaluate the effect of divergent stack design on system performance between 1-3° with 3D CFD model. They investigate the optimum stack divergence angle for power output in the climatic parameters they except for a typical June day.	They claim that the system, which gives a power output of 33.7 kW in the reference case, gives its maximum power output in the 1° divergent chimney design and this value is 70.1 kW. They argue that increasing the angle will reduce the power output of the system again.	1°
Torabi et al., (2021)	In their study using 3D CFD model, they examine the effect of traditional cylindrical chimney and divergent chimney design on system performance. They include the effect of chimney divergence angle on power output in the range of 1-3°.	They report that increasing the chimney divergence angle increases the power output. They claim that the power output, which is 34 kW at 800 W/m² solar radiation in the reference case, will increase to 83.47 kW with a 3° divergent chimney. It is seen that the increase in power output decreases significantly after 1°.	3°
Cuce et al., (2021d)	They evaluate the effect of divergent chimney design on system performance with 3D CFD study. They compare power output in the range of 1-10 AR at 20°C ambient temperature and 1000 W/m² solar radiation.	They claim that the system, which gives a power output of 54.3 kW in the reference case, gives a maximum power output at 3.5 AR and that this value will be 168.5 kW. They state that a further increase in the AR value will have a negative effect on the system.	3.5
Mandal et al., (2024)	They analyse the effect of divergent chimney design on system performance with 3D CFD study. After evaluating chimneys in different designs, they present the effect of divergent chimney on system performance in detail.	They show that the system, which gives a power output of 51.59 kW in the reference case at 302 K ambient temperature and 1000 W/m² solar radiation, will increase by 47% with the divergent chimney design and give a power output of approximately 76 kW.	0.75°

Chimney design is evaluated not only by the chimney convergence divergence angle but also in different ways. Nasraoui et al., (2020) conduct a CFD study that considers the effect of the divergent chimney design and the hyperboloid chimney shape. They claim that the power increase in the divergent chimney design is greater for the ratio of the chimney outlet diameter to the chimney inlet area (DR) of 2 and 5, while the hyperboloid chimney design provides more power output increase for larger DR values. In another study, Bouabidi et al., (2018) present a cylindrical chimney, convergent chimney, divergent chimney, and opposing chimney analysis with the CFD model they validated with a small-scale experimental prototype. They report that the

best performance will be obtained from the divergent chimney. Cuce et al., (2021d) evaluate the effect of the AR value of 1-10 on the power output of the system with a CFD study and present the results in Figure 6.
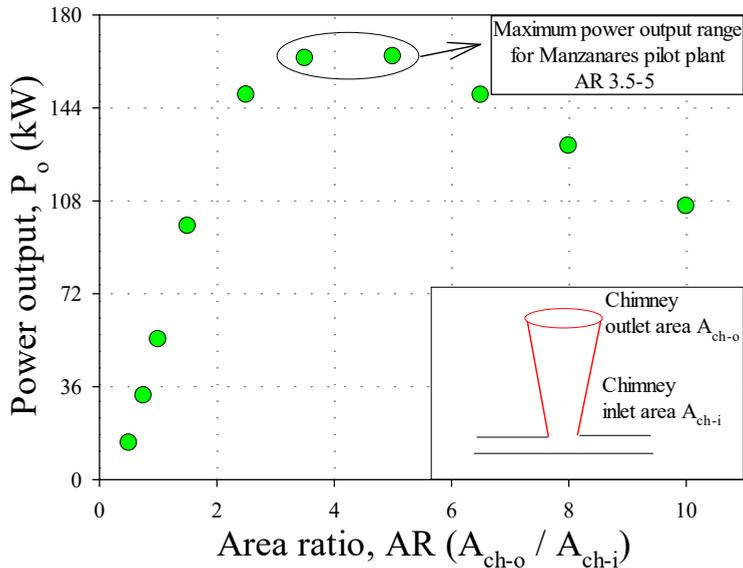

FIG. 6 : Power output for different AR values for Manzanares pilot plant (Cuce et al., 2021d).

Although detailed analysis of geometric parameters is widely available in the literature, it is certain that SCs will continue to attract the attention of researchers due to their multifunctionality and sustainable energy approach. It is especially important to evaluate the system components together rather than separately. Najm and Shaaban (2018) draw attention to this situation by claiming that a change in one of the geometric parameters will cause a change in other parameters for optimum power output, such that when the chimney height increases, the optimum value of the collector size for maximum power output and efficiency will change. Therefore, it is important to evaluate the geometric parameters together instead of analysing them separately.

3   Conclusion

This study focuses on the effects of chimney design on system performance. It aims to provide a perspective by focusing on power output and air velocity. When the chimney is evaluated in terms of height, diameter, and design, it is seen that it causes critical effects on system outputs. Although it is widely available in the literature, it is important to present the existing data by making comparisons to guide future studies. The critical findings obtained from the study can be presented as follows :

- Although there are numerous studies on SCs performance in the literature, the effect of some system parameters on system performance is controversial.

- The chimney is the driving force of the system and directly increases the power output. In fact, increasing the chimney height also increases the power output. However, some researchers believe that there are limits to increasing the chimney height according to the system geometry.

- The chimney diameter, like the chimney height, also affects the system performance. There is a common opinion among researchers that the optimum chimney diameter for the Manzanares pilot plant is.

- Compared to the traditional cylindrical chimney, the divergent chimney design increases power output, so much so that some researchers claim that the power output of the Manzanares pilot plant could be increased 10-fold with the divergent chimney design.

- Although there is a common view that the divergent BCA design increases power output, there are debates about the divergent design that gives maximum power output.

- CFD is more useful in analysing and visualizing outputs such as temperature, pressure, air speed within the system. It can also be said to be more advantageous than theoretical studies since it offers the opportunity to evaluate the system.

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