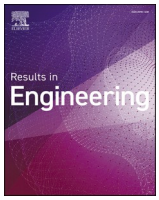
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Review article

Performance comparison of cylindrical and diverging solar chimney power plants

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ABSTRACT

Solar Chimney Power Plants (SCPPs) are promising renewable energy technology that utilize solar energy to generate electricity. The conventional cylindrical SCPP, as exemplified by the Manzanares prototype, produced 50 kW of power with a 194.6 m chimney and a 244 m collector. However, divergent SCPPs demonstrated higher efficiency. The purpose of this study is to analyze and compare the key performance parameters of these two plants by examining the current experimental and simulation findings. Prior reviews have also not gone much into the impact of chimney's divergence angle or area ratio (AR) on the airflow dynamics. With an optimal area ratio (AR) of 4.1, they achieved a power output of 168.5 kW showing an increment of about 237 % over cylindrical designs. Other studies showed that increasing chimney height of a small sized divergent SCPP from 4 m to 8 m could lead to improve the temperature change by 513.3 % (from 1.5 °C to 9.2 °C) that caused the power output to increase by 252 %. Numerical simulations indicated that a 38.9 m divergent chimney can match the power output of a 194.6 m cylindrical chimney and reduce construction costs by 70 %. Additionally, Bell-mouth integration could further enhance the airflow by 6–7 % and boosts turbine power by 21 %. In general, this review highlights the critical role of geometric optimization for maximizing plant's efficiency. Unlike previous reviews, this study gives more of quantitative analysis. Moreover, the possible occurrence of backflow and scalability challenges which could occur in non-optimized systems are also discussed. Hence, the results of this review give an insight for upcoming SCPP designers to develop efficient and cost-effective plants.

1. Introduction

Solar energy can be harnessed through two main technologies to generate electricity: solar photovoltaic (PV) and solar thermal plants. While PV systems which essentially use semiconductor based devices directly convert sunlight into electricity, solar thermal power plants rely on their mechanical devices to transform solar power into electrical power by generating high temperature working fluid. Among thermal options, Solar chimney plants (SCPP) present low temperature alternative that utilized a simple configuration consisting of a chimney, solar collector and turbine. These plants generate power through buoyancy driven airflow that is created by solar radiation heated air under the collector, which then drives the turbine/s located at the chimney base.

The basic idea of harnessing hot air for draft dates back to Leonardo Da Vinci (around 1500), who proposed to extract hot air for roasting food. However, the idea of SCPP was initially proposed by Isidoro Cabanyes in 1903 while just after him Günther published the concept. Numerous inventions have been made since 1975 in the USA, Australia, Canada, Israel, and other nations [1,2]. The most significant historical milestone occurred in 1981/1982, when the first operational prototype of 50 kW SCPP was built by the 'Spanish Utility Union, Electrica Fenosa' in Manzanare [2–4]. This plant featured a chimney length of 194.6 m with a collector diameter of 244 m to generate about 50 kW electrical power, marking the first large-scale experimental validation of the SCPP concept.

Despite their simple design and low operational costs, the lower conversion efficiency is the main challenge of these plants. This remains their primary limitation. However, their minimal maintenance requirements and potential for operation in arid or remote areas have continued to attract researchers, focusing particularly on performance improvement [5,6]. Due to their high construction costs, many researchers prefer numerical methods like CFD methods for a prior performance system evaluation [7,8]. Optimizing the basic parameters such as chimney height, collector diameter and above all divergent angle (system configuration) [9], significantly boosts the power output.

This study focuses on the performance optimization of SCPPs, with a

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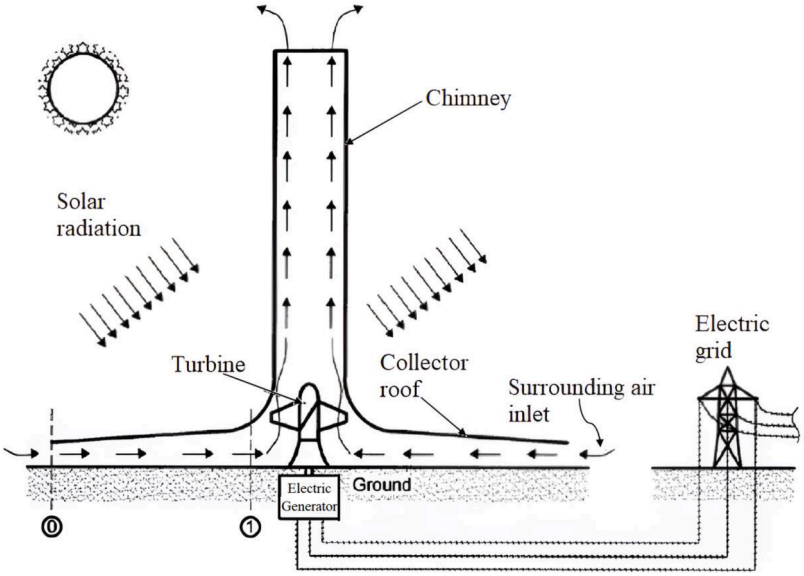


Fig. 1. Schematic illustration of the solar chimney plant's concept [18].

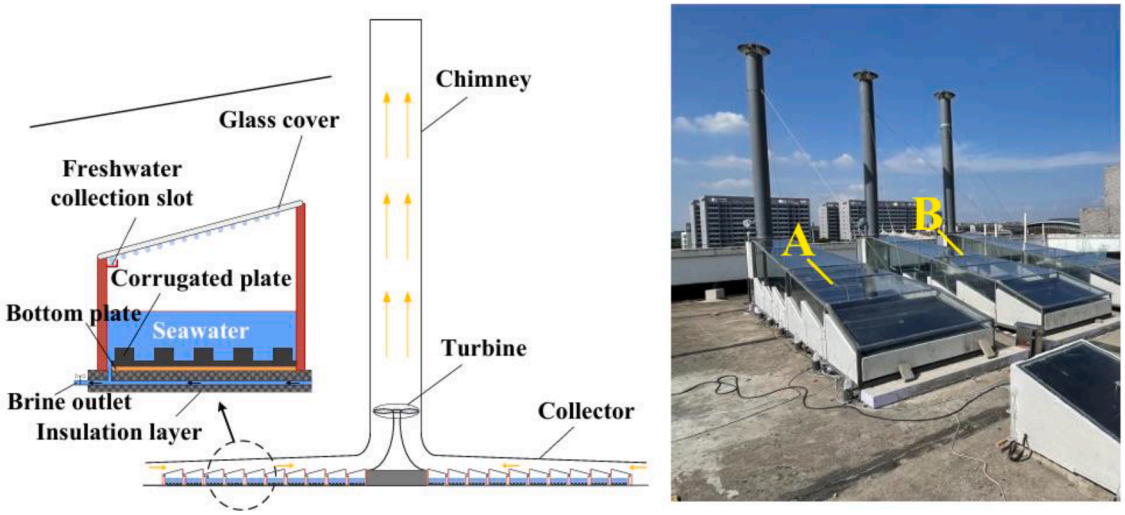


Fig. 2. Corrugated plate enhanced SCPPCD test setups [23].

particular emphasis on the effects of system geometry and material properties of the collector's absorber surface. It investigates critical design parameters such as chimney height, collector diameter and inclination angle of the absorber. Additionally, it analyzes the influence of thermal conductivity, specific heat capacity, and density of the collector surface material on airflow dynamics and system efficiency. Through CFD simulations, the study evaluates how these parameters affect air velocity and collector efficiency under various solar radiation conditions.

Most of the previous review reports focused on isolated parameters without optimizing them holistically. This reviews bridges this gap by employing mainly computationally analyzed studies to identify optimal values by critically reviewing cylindrical and diffused SCPPs that enhance buoyancy-driven airflow and system efficiency. This will contribute to improve low efficiency limitations and guiding cost effective design for future SCPP deployments, especially in arid regions.

2. Description of SCPP

A chimney, a solar collector and a turbine make up the SCPP, Fig. 1. The collector is where the air gets heated. It is made of a glazing (transparent roof) and an absorber surface. The chimney's pressure gradient draws air upward, while the suction from the updraft tower improves the buoyancy of the hot air [13–16]. Finally, the wind turbine and generator use the heated air to generate electricity [17].

Omar Ardila et al. numerically evaluated buoyancy driven ventilation system using a solar chimney that showed airflow rates between 10 m^3/h to 40 m^3/h depending on solar radiation intensity and chimney geometry. Their result showed that temperature difference between indoor and outdoor air was reaching up to 15 °C. This enhanced the buoyancy effect significantly. They have reported that solar chimneys can contribute about 40 % of the required ventilation rates [19].

Experimental results showed that a considerable quantity of thermal energy was being lost during the day beneath the solar collector. Integration of a thermal storage unit can further increase energy production by 35 % [20,21]. Some of the popular heat storage methods currently used are sand gravel and black tubes filled with water, Fig. 2 [7]. An experimental and theoretical studies were conducted in the north-western part of Libya to investigate the performance of SCPP [22].

ZUO et al. integrated a corrugated plate enhancement material

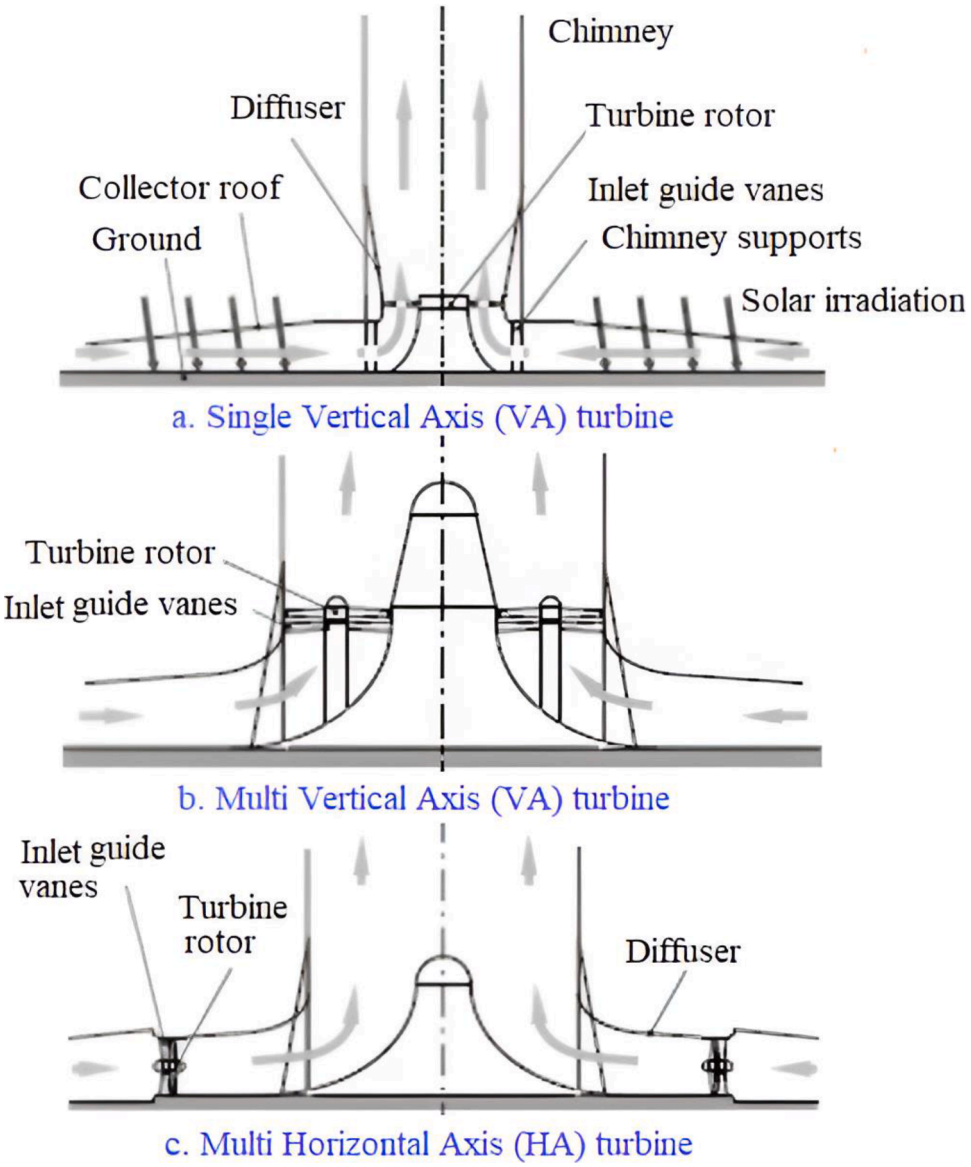


Fig. 3. Single and multiple vertical and horizontal axes turbines [24].

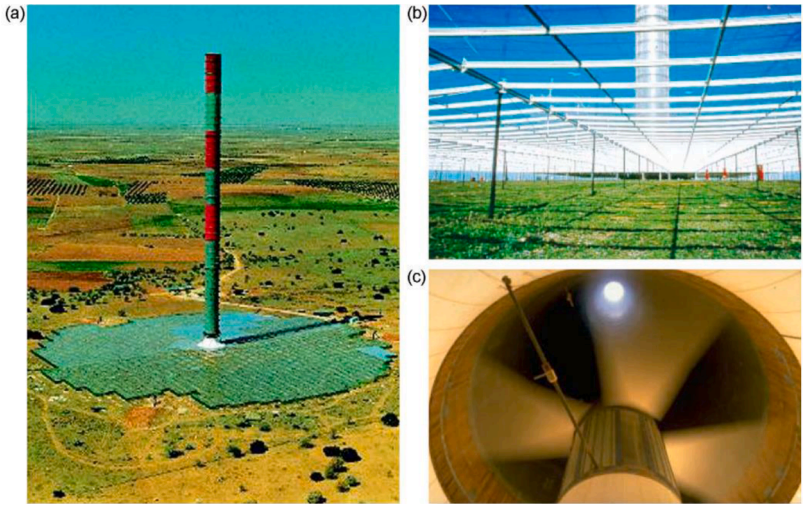


Fig. 4. The first SCPP, Manzanres [7].

mainly to strengthen the heat storage and uniform heat distillation without affecting the working principle of the system, Fig. 2. During the 14:00–18:00 h, their testing results revealed that the airflow temperature rise, chimney outlet flow rate, and negative chimney pressure reached above 12.80 %, 2.80 % and 4.60 % respectively. As a result, the rate of daily solar energy usage rose from 28.81 % to 33.9 % that improved the power generation by 5.24 % [23].

Fig. 3 provides a clear illustration of the SCPP's operating principles. As shown, air that has been heated by the solar collector enters the chimney passing radially through the pillars supporting it. The pillars that have airfoil shape are placed along non-radial chord lines act as inlet guiding vanes. The axial flow turbine that is most frequently employed in solar chimney plants shares many characteristics with both wind turbines and gas turbines. It has more blades than the typical wind turbines but less number of blades than axial flow gas turbines. The rotor blades are adjustable, just like those found in wind turbines, but the flow is enclosed as in gas turbines. It is possible to control the air flow and power output of such plants simply by adjusting the blade angle [24].

In Manzanares, Spain, SCPPs with different arrangements have been investigated, Fig. 4. A single vertical axis turbine without inlet guiding vanes was one of them. A large-scale solar chimney has also been proposed to use a similar single vertical axis turbine configuration that leverages the chimney support structure as inlet guide vanes [25,10].

Other suggestions include the employment of various combinations of vertical axis turbines and turbine designs with a single pair of counter-rotating rotors, with or without inlet guiding vanes. The study describes a proposed radial turbine that would be installed at the bottom of the SCPP. The prototype is sizable. The performance of the turbine was also theoretically evaluated using 3-D CFD simulations [25].

3. Methodology

3.1. Review inclusion and exclusion criteria

The main objective of this study is to critically analyze recent experimental and simulation findings in the field of SCPPs and synthesize key performance metrics across different design types. This review thus focuses on gathering, analyzing, and comparing performance indicators such as power output and efficiency. Accordingly, a systematic review of recent experimental and simulation findings on SCPPs has been executed. The systematic review of SCPP studies followed an overview of the following procedures that have been set out to give critical review.

3.2. Literature selection and screening

Literature selection: a systematic search across academic databases was conducted to review recent studies published within the last ten years, with tropical regions given top priority. Inclusion criteria were high-quality peer-reviewed journals. Exclusion criteria include publications without empirical data, very old publications unless they are very important, publications with unclear methodologies, and non-peer-reviewed articles.

Screening publications: Abstracts and titles were screened for relevance to the topic of SCPP. Full texts of relevant studies were assessed for their appropriateness in relation to the objectives of the review. The selected articles were identified by the presence of specific experimental data, the validation methodologies used and the quality of the journal in which they had been published.

3.3. Data collection, organization and classification

More emphasis was placed on data extraction of key performance indicators from the works studied, including: power output, efficiency, airflow velocity. The gathered data were organized to classify studies by design type such as different configurations and components. Finally, the extracted key performance metrics were compiled to compare the average performance across the different types of SCPPs.

3.4. Quality, credibility, synthesis and discussion

The review gave priority to studies that provided detailed experimental data, simulated and validated results that were published in highly reputed journals. Moreover, it analyzed the performance metrics of different design types focusing on improving the overall SCPP performance while addressing trade-offs and limitations. To guarantee applicability, studies carried out in areas with climates comparable to tropical regions were given top priority.

4. Results and discussion

The power output and efficiency of the plant are anticipated using intricate mathematical modeling for a wide range of design and operational parameters relating to the fluid flow and heat transfer characteristics. The physical dimensions of the plant, such as the chimney height, chimney diameter, collector height, thermal storage, and plant configuration, have a major influence on the performance of solar chimneys. Furthermore, the plant's power output and efficiency are significantly impacted by external factors such as ambient temperature and solar irradiation. The impact of these factors on system performance is examined here, with a particular emphasis on chimney configuration.

4.1. Impact of temperature and irradiance on performance

The surrounding temperature affect the key performance metrics such as mass flow rate, velocity, hot air temperature, power output and overall efficiency of the plant. A passive driving force occurs by density difference caused by the temperature difference between the air inside the collector and the surrounding air. Inside the collector, the buoyancy effect caused air to converge along the collector and move towards the chimney inlet.

Cuce et al., evaluated the performance of a SCPP using 3D computational fluid dynamics (CFD) for different surrounding temperatures. At 1000 W/m^2 solar irradiance, the power output was seen to be around 49.7 kW and 8.4 kW respectively for 293.15 K and 320 K ambient temperatures [21]. A CFD analysis revealed that when the ambient air and irradiance were maintained at 290 K and 800 W/m^2, respectively, the air temperature rose by 67.3 K. With the same irradiance and a surrounding temperature of 300 K, however, the rise was by 64.88 K. On the other hand, keeping the temperature at 300 K and varying the solar radiation from 200 W/m^2 to 800 W/m^2 the air velocity increased from 6.67m/s to 11.10 m/s [26].

4.2. Impact of collector type and dimension on performance

Different studies revealed that collector plays great role in the performance solar thermal plants. A recent studies by M. S. Saleem and N. Abas introduced a solar assisted polygeneration system optimized via TRNSYS-GenOpt. They achieved up to 74 % thermal collector efficiency [10]. For solar chimney plants, the impact of the collector roof angle on the solar chimney was studied using convergent, divergent, and zero-degree collector roof angles [27,28]. A. Koonsrisuk, et al. has shown how the dimensions of the collector affect the pressure drop as a result the system performance [29]. F. M. Hussain and F. A. Al-Sulaiman reported utilizing reflectors incident more solar rays to the absorber and improve the efficiency and power output. The increased mass flow rate is what causes the increase in power output [30].

Das and Chandramohan have also optimized the collector inclination angle keeping the chmney height at 8 m [31]. Increasing the collector inclination angle from 25° to 30° dropped the power output from 0.38 to 0.11 W and decreased the efficiency from 0.0035 to 0.00103 % [31]. An indoor experimental analysis has been conducted to compare

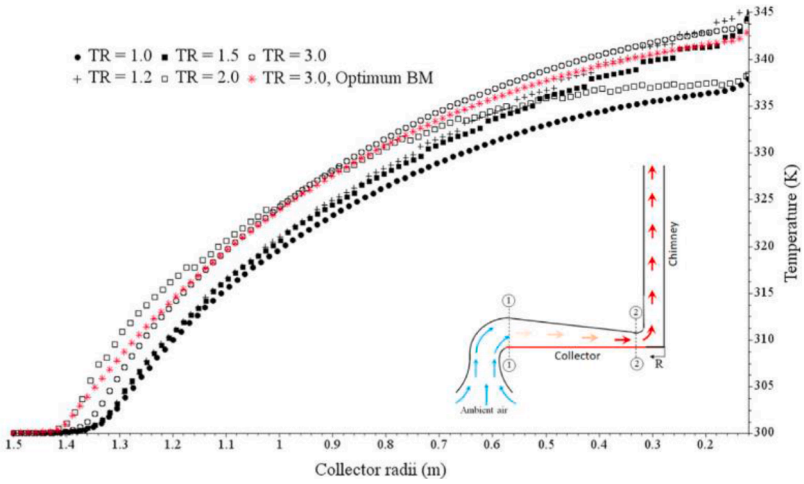


Fig. 5. Temperature variation along collector radius [34].

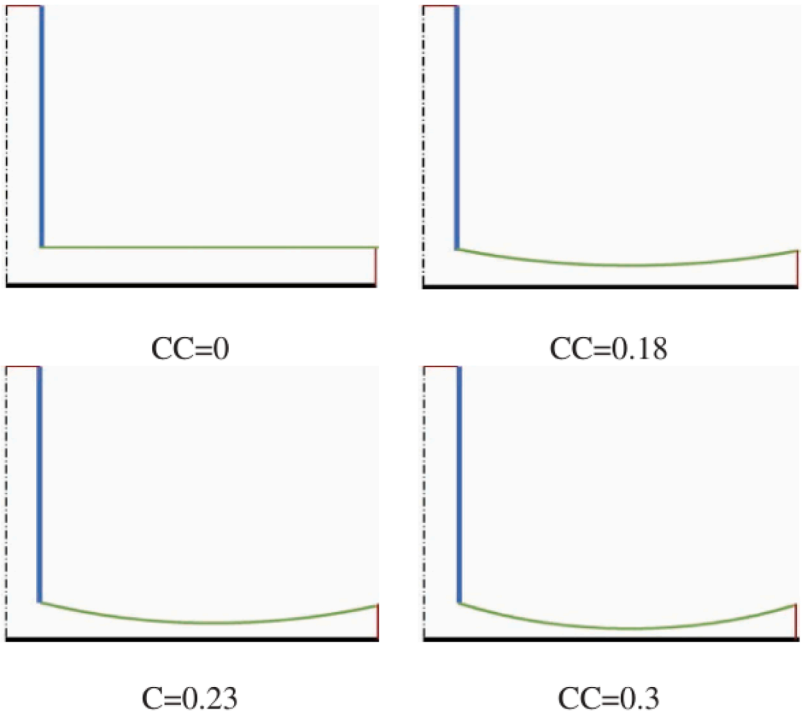


Fig. 6. Schematics of divergent chimney with sloped collector [35].

convergent, divergent and flat type collectors on 194 m chimney height plant. The divergent collector improved the velocity by only 8.6 % while the flat by 21.2 % and the convergent by 25 % [32]. Ahirwar and Sharma claimed that when the collector is convergent up to 6°, the suction effect and heat transfer from the chimney are improved. However, if this angle is further raised, recirculation takes place inside the collector and causes the performance to drop [33]. The CFD finding of M. Sundararaj et al. (2022) also revealed that the convergent collector that causes the mean temperature of air to raise by 18 K improved the updraft effect to increase [41].

P. Singh, A. Kumar carried out an investigation on divergent types plant by integrating a bell mouth at the collector's inlet, Fig. 5. Integrating the bell mouth in the system, increases the flow velocity by 6 to 7 % and the turbine power output increased by 21 %. They further examined 90° upward, 90° downward, and horizontal bell-mouth configurations. Their result demonstrated that the upward and downward oriented bell-mouths had continuous flow velocity while for the horizontal display it was varying. The optimal design with bell-mouth integration that increased the air velocity by 270 % had a coefficient of radius ratio (CORR) of 2 [34].

The inclination angle of the absorber surface plays a crucial role in the system efficiency.

A CFD modeling results reported by O. Drame, Z revealed increasing the tilt of the collector surface from 0° to 15° enhances the air velocity at the chimney's base from 8.86 m/s to 18 m/s. This15° was the optimal inclination since tilting it further reduced the velocity, due to the boundary layer separation [12].

Moreover, H. Nasraoui, et al. have studied how collector's concavity ratio affects air flow velocity and system power output, Fig. 6. A velocity of 2.5 m/s that causes 112 % increment of power were achieved with a concavity ratio of 0.3 as compared to the zero-concavity ratio [35].

Furthermore, the CFD simulation results reported by E. M. Abo-

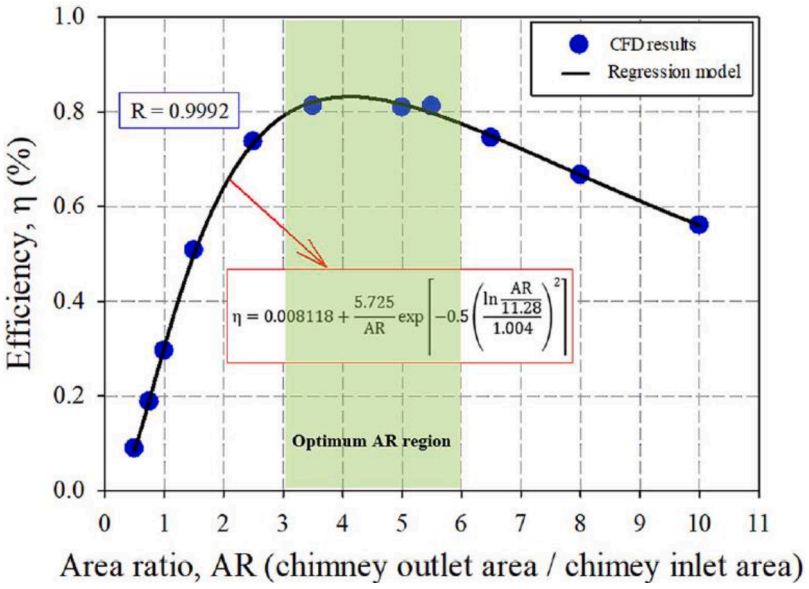


Fig. 7. System efficiency as a function of AR with the optimum AR [52].

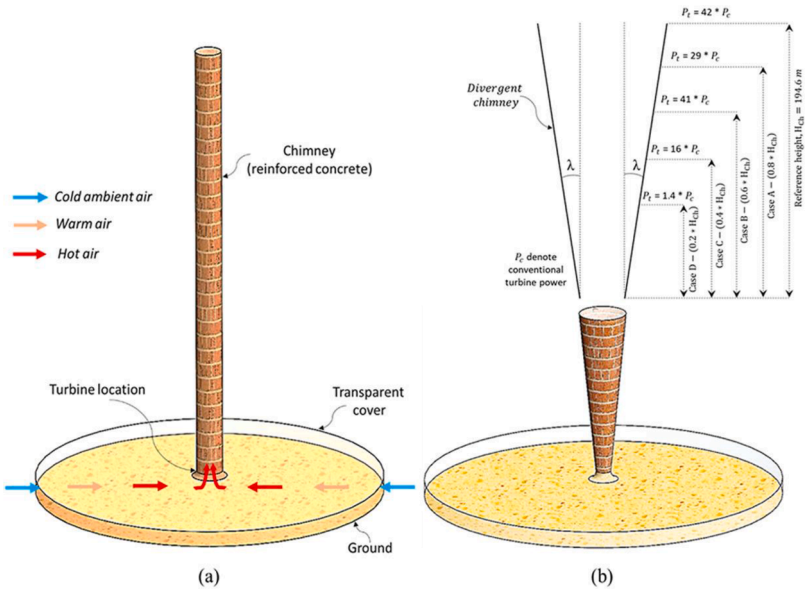


Fig. 8. Estimated size of equal performing cylindrical and diverging SCPP by Pratap et al[53].

Zahhad, et al. revealed that material properties of the ground surface were also found to significantly influence thermal behavior and performance of the system. Their report showed a thermal conductivity of 0.1 W/m·K, a specific heat capacity of 2750 J/kg·K and a density of 2000 kg/m3 are to be optimal values. This was because these parameters minimize heat loss, maximize energy retention and enhance the buoyancy effect and ultimately to increase the power output of the system [11].

S. Pradhan, et al. (2021) have also studied a system were baffles were integrated in the system. A total of six different baffles were integrated in the models [17]. In addition to the power output change, the presence of baffles also changed the temperature, pressure and velocity fields [36].

4.3. Impact of chimney height on performance

Chimney height and collector area are the two primary factors that affect power generation. As reported by G. Xu, et al. (2011), one of the system's main source of energy loss is the enormous outflow of hot air from the chimney outlet [37]. However, a larger chimney height increases the pressure difference via the stack effect, enhancing the system's efficiency. If the chimney height is lower, an increase in the collector area can serve as a substitute [29,38–41]. However, depending on the configuration type and the scale (size) of the plant there is an optimal height value after which the performance drops [42].

According to the literature, A chimney height of up to 1000 m may be required for an economically viable Solar Chimney Power Plant (SCPP). Jianlan Li et al. (2016) reported that the power generation efficiency improved linearly from 0.08 % to 0.37 % when the chimney height growing from 100 to 400 m [43]. Toghraie et al. (2018) numerically assessed the cylindrical chimney's performance by varying its height from 50 to 400 m and reported an improvement in efficiency from 0.063 to 0.83 [44]. Another study has been conducted by varying chimney height from 3 to 8 m, the velocity of air at the chimney base increased

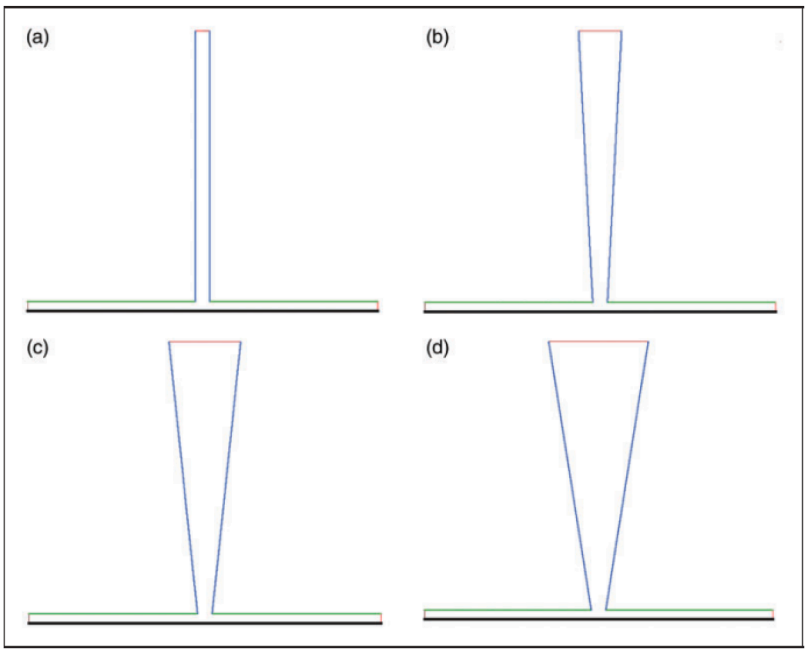


Fig. 9. The considered configurations. (a) α = 0°, (b) α = 3°, (c) α = 9°, (d) α = 9° [55].

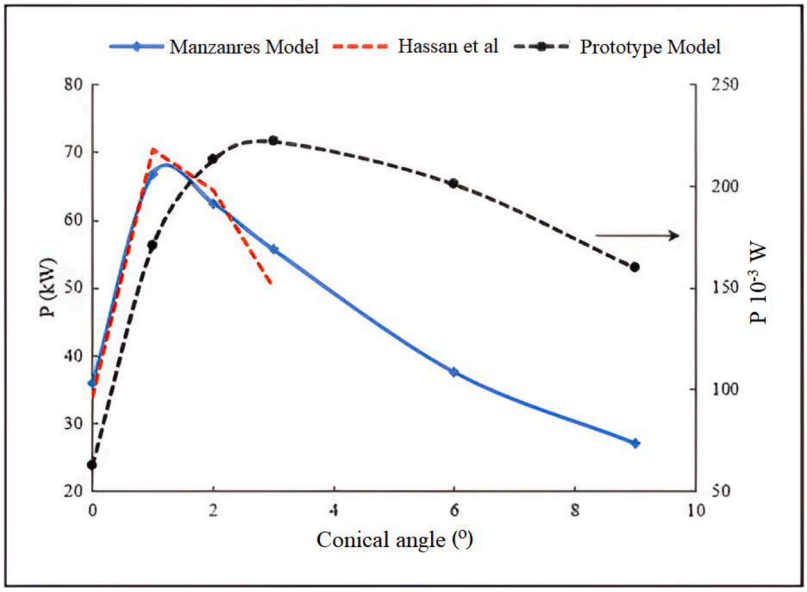


Fig. 10. Effect of the conical chimney angle on the power output of DSCPP system [55].

from 1.617 m/s to 2.338 m/s [31]. Another study that was executed on small-scale chimney plant by varying the chimney height between 0.1 m and 2 m, indicated the optimum chimney height to be 1.5 m [45]. As reported by R. Prasad and M. R. Ahmed (2023), an increase in chimney height from 4 m to 8 m lead to raise the temperature difference from 1.5 °C to 9.2 °C (with a 513.3 % increment). At last, a 27 % velocity increment has been achieved that resulted in a 252 % increase in power production, 0.79 W to 2.87 W[46].

4.4. Impact of chimney configuration on performance (Comparison between cylindrical and divergent chimneys)

Different researches that compare the conventional Manzanares power plant with the diverging chimney have been done. M. Sundararaj et al. (2022) revealed such configuration change may rise mass flow rate by up to 50 % [19]. To enable a better understanding of various shape characteristics, the effects of divergent and convergent chimney angle and chimney height were explored by different researchers [47]. Results were contrasted with a reference case that featured a cylindrical chimney shape. Since the diameter of the divergent kind of chimney rises slightly with height, the low static pressure at the chimney entrance is affected, which significantly impacts the air velocity value and encourages more airflow within the system [48]. Four different chimney configurations: small, wide, conical and hyperbolic were compared by H. Nasraoui et al. (2019), who confirmed that the hyperbolic chimney outperformed the others [49]. Since the diameter of the divergent kind of chimney rises slightly with height, the low static pressure at the chimney entrance is affected, which significantly impacts the air velocity value and encourages more air to flow within the system [48]. S. Okada et al. (2018) claimed using a divergent chimney with a 4°

Table 1
Cylindrical chimneys (Divergence Angle = 0°).

Study	Chimney Height (m)	Collector Diameter (m)	Efficiency (%)	Power Output (W)	Key Insights
Haaf et al., 1983, [3,4]	194.6	244	0.53	50,000	Experimental baseline study; demonstrated reasonable cost and performance for a large-scale SCPP.
Li, Guo, and Huang, 2016, 2016 [43]	200	540	0.18	45,000	Numerical study; explored the relationship between power output and geometric parameters with a heat storage layer.
Attig-Bahar et al., 2019, 2019 [20]	195	244	0.08	35,000	Numerically Highlighted the impact of thermal storage, with a 35 % improvement in efficiency compared to systems without storage.
Toghraie et al., 2018, [44]	50 to 400	50 to 400	0.063 to 0.83	24,000 to 313,500	Numerically evaluated the effect of varying chimney height and collector diameter, identifying optimal configurations for power and efficiency.
Bansod, 2020, [26]	0.5 to 2	1.8	0.0046 to 0.0376	Not reported	Experimentally investigated small-scale prototypes, emphasizing the role of chimney height in power production.
Yapici et al., 2020, [54]	3.5	4	Not reported	0.25	Focused on small-scale systems, numerically showing very low efficiency due to the limited scale and height of the chimney.
Cuce et al., 2020, [21]	194.6	244	Not reported	49,000	Examined numerically the impact of solar radiation and ambient temperature on the performance of a large-scale chimney system.

divergence angle enhances the power output by around three times as compared to a straight chimney plants [50].

As reported by S. Hu et al., there is an optimum value of small outlet-to-inlet Area Ratio (AR) for maximizing efficiency. The proposed diffuser type tower generates wind power with a velocity 1.38 to 0.44 times higher than conventional cylindrical towers resulting in 2.6 to 3.0 times greater power output. They revealed the start of performance deterioration after a certain point because of back flow and stall formation which lowers the buoyancy, pressure potential and even temperature of the air [51].

CFD results on the comparison of solar chimney plants were reported by E. Cuce et al. in 2021. As illustrated in Fig. 7, they revealed that the mass flow rate was 1122.1 kg/s for the reference case AR value of 1 and 11,629.1 kg/s at the optimal AR value of 4.1. For AR = 1, the dynamic pressure difference across the turbine was −109.8 Pa, while for AR = 4.1, it was −232.3 Pa. At the optimal situation, the minimum static pressure was −386.6 Pa. The power output and efficiency were 54.3 kW and 0.29 % respectively for AR of 1, however in the optimal case, they increased to 168.5 kW and 0.83 % respectively. Base on this, they figured out that the optimal AR falls between 3 and 6[52].

Pratap et al. (2023) revealed that conventional chimney's 50 kW power output at 194.6 m height can be obtained at 20 % of its height in a divergent chimney as shown in Fig. 8. According to the research, divergent chimneys achieve 42.14 times the power of a traditional power plant at the same chimney height of 194.6 m [53].

Yapici et al. (2020) reported their findings on different chimney configurations by varying the chimney heights from 1.5 m to 3.5 m. The diameter of the chimney at the entrance was kept to be 0.25 m while the collector radius was changing from 0.1 m and 1.5 m. Among these configurations, the diverging chimney plant performed better by generating a 0.54 W power output. Increasing the collector radius has a substantial impact on improving air velocity, temperature, and plant power output while an increase in collector diameter up to 4 m raised the efficiency (beyond that it decreases) [54].

As show in Fig. 9, Nasraoui et al. (2019) reported the effect of diverging angle of chimneys (β = 0°, 3°, 6°, and 9°) on velocity and temperature. Their results showed diverging angle considerably impacted on the air velocity and the power output. The optimal diverging angle was 3° They have reported that as the angle further grows, backflow resulting from the eddy effect induces stall and causes a drop-in pressure. Varying this angle had negligibly effect on air temperature [55].

Fig. 10 illustrates the comparison between their results with Manzanres' and Hassan et al's results. Likewise, a study was conducted on the chimney divergence angle ranging from 1° to 5°

Similar study conducted by P. Das and V. P. Chandramohan (2021) showed a maximum velocity of 3.53 m/s could achieve at 2° divergent angle [56].

Xu and Zhou reported focusing on how the backflow and stall formed in the chimney and affect the power output. They took Chimney Outlet to inlet Area Ratio (COAR) of 8.7, 11.9, 15.5, and 24.2. At 8.7 COAR, the air flows uniformly with no stalling or backflow. Further raise in COAR, resulted in the formation of stalling, backflow and vortices that caused lower performance. As a result, their report showed that divergence angle optimization be required before manufacturing [57].

For 180 m and 210 m chimney heights at four collector slops of 2°, 4°, 6°, 8° and 10°, Ahirwar and Sharma (2019) optimized to get the best performing divergence angle between 2°, 4°, and 6°. Lastly, they concluded that the optimal divergent angle to be 2° where the power increases by 107.7 % as compared to the zero chimney diverging angle [33].

In their experiment, Jawad et al. used three cylindrical and three divergent small-scale SCPPs with chimney heights of 1, 1.5 and 2 m. The area of collector was 0.8 m^2. The velocity is high in the shortest chimneys due to no loss and a tiny cross- sectional area. Furthermore, at 1 m, the velocity of the divergent and cylindrical chimneys was 0.994 m/s and 0.820 m/s, respectively. They also investigate the influence of mass flow on the cylindrical and divergent chimney heights. It indicates an increase in both situations due to the rise in cross- sectional area. A 2 kW electric heat load was used to imitate solar radiation. The power increment of the 1.5 m chimney height cylindrical plant was 11 % as

Table 2
Divergent chimneys (Divergence Angle > 0°).

Study	Chimney Height (m)	Collector Diameter (m)	Divergence Angle (°)	Efficiency (%)	Power Output (W)	Key Insights
Pratap et al., 2023, [53]	38.9	Not reported	5.22	0.53	50,000	Demonstrated equivalent power output to taller cylindrical chimneys with reduced height, showing cost-performance benefits using numerical analysis.
Das and Chandramohan, 2019, [31]	7	3.5	1 to 5	0.0057 to 0.0077	0.9	Highlighted numerically a modest increase in velocity and efficiency with divergence angle.
Nasraoui et al., 2019, [55]	2.59	3.7	3	Not reported	2.3	Studied experimentally and numerically the impact of collector concavity and divergent chimney designs on airflow and power output.
Xu and Zhou, 2018, [57]	194.6	244	–	Not reported	231,700	Numerically evaluated the coefficient of area ratio (COAR), finding an optimal value of 8.7 for high efficiency and power output.
Ahirwar and Sharma, 2019, 2019 [33]	190	244	2	Not reported	71,520	Numerically investigated collector slope and divergence angle, identifying increased power output with optimized geometry.
Jawad et al., 2021, [58]	1.5	Not reported	2	Not reported	183	Laboratory experiments on small-scale divergent chimneys; noted the impact of divergence on theoretical power output.
Cuce et al., 2021, [52]	194.6	244	5.32	0.83	168,500	Numerically found an optimal area ratio of 4.1, resulting in significantly improved efficiency and power output compared to cylindrical designs.

Table 3
Performance comparison of cylindrical and divergent SCPPs.

Chimney Type	Range of Efficiency (η_{scpp})	Performance Relative to Manzanares Baseline ($\eta_{scpp}/\eta_{scpp.Maz}$)	Key Insights
Cylindrical	0.0046 % - 0.53 %	0.0086 - 1.0	Their overall efficiency is lower. The taller the chimney is and the bigger the collector's diameter is, the better the performance. In addition, smaller plants are usually less efficient; consequently, cylindrical systems are very dependent on size.
Divergent	0.0057 % - 0.88 %	0.01 - 4.634	Their improved airflow and less pressure losses result in a relatively higher efficiency. They work optimally at certain divergence angles between 2 and 5 degrees. At a relatively lower chimney height (about one-third of the cylinder one), they generate equal power.

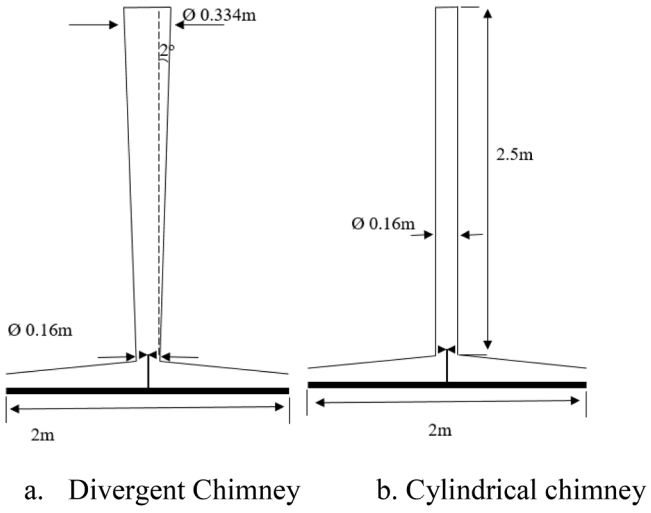


Fig. 11. Schematics of SCPP.

compared to the 1 m chimney height, whereas the divergent plant's power increment was 37.15 %. In both situations, the maximum theoretical power was reached at a chimney height of 2 m[58].

P. M. Cuce et al. compared the conventional pilot power plant at Manzanares to their plant that had a convergent collector and a divergent chimney. Using a CFD tool, they illustrated how design changes affect basic parameters like air velocity, pressure drop and power output. The power output was 146.34 kW, about three times the conventional 50 kW due to the 102 % rise in pressure drop [59].

Reviews of the literature generally indicated that, in contrast to cylindrical towered plants, the mass flow rate decreases in converging towered layouts due to an increase in top velocity. The maximal velocity (kinetic energy) of diverging towers, however, is found at their base not at their top. They can therefore do mechanical work with greater energy potential than others. Additionally, it is necessary to optimize the divergence angle for various geometrical factors prior to manufacture in order to get better performance. Tables 1 and 2 provide a summary of the performance outcomes of the divergent and cylindrical chimney plants.

The reviewed articles highlighted the important trends required in solar chimney power plants (SCPP) designs. Cylindrical chimneys generally exhibit lower efficiency and power output as compared to divergent designs for similar collector sizes. Geometric optimization plays a critical role, as studies like Cuce et al. (2021) emphasize the importance of area ratio and divergence angle in maximizing mass flow rate, power output, and efficiency. The best performance occurs in large-scale configurations, where both the collector and chimney dimensions are optimized. Divergent chimneys show significant efficiency improvements when the divergence angle is optimized in between 2° and 5° to achieve equivalent or better performance with shorter heights that leads to the reduction of construction costs. Scaling SCPPs has to be considered carefully since studies revealed that smaller plant discussed by Bansod, 2020 and Yapici et al., 2020 significantly lowered efficiencies. They have also highlighted the difficulties of scaling down SCPP systems. Finally, the incorporation of thermal storage as reported by different researchers like Attig-Bahar et al. (2019) offers substantial performance improvements for practical applications Table 3.

The geometrical size and configuration type of SCPPs are crucial for optimization in attaining higher power output and efficiency. As

reported by Haaf et al., cylindrical chimney plants benefit from taller height chimney and larger collector diameters [3,4]. Nearly 50 kW power output with a 194.6 m chimney and a 244 m collector diameter was achieved. However, such big plants lead to high construction costs and structural challenges. On the other hand, plants with divergent chimney performed better particularly at the optimal divergence angle that ranges between 2° and 5°. Das & Chandramohan revealed that this was due to the significant increase in air velocity [31]. Cuce et al. also reported the possibility of generating up to 168.5 kW power having 194.6 m chimney height with an area ratio (AR) of 4.1 [52]. Furthermore, Xu and Zhou reported having similar chimney height the highest power output of 231.7 kW having 8.7 as an optimal coefficient of area ratio (COAR) [57].

The better performance of divergent chimney plant is mainly due to the increase in velocity as a result of a significantly reduction in backflow that enhanced uniform airflow. Pratap et al. demonstrated that a 38.9 m divergent chimney height can match the power output of a 194.6 m cylindrical chimney [53]. This highlighted the potential of divergent SCPPs for cost reduction. In general, the cylindrical SCPPs demonstrate a broad range of power output (0.0046 - 313.5 kW). The reviews showed efficiency (η_{scpp}) in the range of 0.0046 % - 0.53 %, with a performance relative to the Manzanares Baseline (0.0086 - 1.0). In contrast, divergent SCPPs exhibit a comparable range, with power output varying between 0.68 and 231.7 kW, with efficiency range spanning 0.0057 % - 0.88 %, and a performance range relative to the Manzanares Baseline (0.01 - 4.634).

4.5. Experimental investigation of SCPPs: case study at AAU

Two small-scale SCPPs of the cylindrical and divergent types, Fig. 11, have been built and tested at College of Technology and Built Environment, Addis Ababa University. The divergent angle of the divergent plant was 2°. This experimental analysis aimed to make the literature review more practical.

The purpose of the test was to determine how power output and efficiency were affected by the type of chimney configuration and its size. The key findings from this experiment highlighted that air velocity and area ratio probably the cross-sectional area of the chimney played a very important role in the performance. The theoretical data also showed that increasing the chimney height from 1.5 m to 2.5 m increased the power for both types of chimneys by about 66.6 %. This showed that the configuration and height of the chimney are very important variables for the enhancement of the system's efficiency and its output.

The case study results provided empirical support for the numerical and experimental claims in the literature review. Below are the key validation points: The literature review stated that a divergent chimney achieves significantly higher power output and efficiency than a cylindrical one where an optimized divergent chimney with a 4.1 area ratio reached 168.5 kW (237 % improvement) as compared to the 50 kW. The results of the case study also demonstrated the advantage of the divergent chimney, which produced 23.6 W of power as compare to 5.29 W for the cylindrical type. The efficiency results were 0.444 % for cylindrical and 1.9 % divergent types. The review results claimed that increasing chimney height improves output. The case study also supported this trend: raising chimney height from 1.5 m to 2.5 m increases power output by 66.6 %. Though the conducted experimental scale was smaller, the observed percentage improvements mirror (support the reliability of) the large-scale theoretical and experimental predictions reported by different researchers.

5. Conclusion

This review provides a comprehensive comparison between cylindrical and divergent SCPPs. It shows their performance differences in terms of efficient and on power output that occurred mostly due to configuration and dimensional changes. The research findings showed how divergent chimneys outperform cylindrical chimneys due to their ability to enhance airflow by reducing backflow. The conventional cylindrical SCPP as evidenced by the Manzanares prototype, achieved a 50 kW power output and a 0.53 % efficiency with a chimney height of 194.6 m and a collector diameter of 244 m. On the other hand, studies have revealed that a divergent chimney with an optimal area ratio (AR) of 4.1 can generate 168.5 kW that made a 237 % improvement over the Manzanares plant. Further study even revealed that a divergent chimney might meet the 50 kW output of the conventional cylindrical chimney with a height of only 38.9 m. This greatly decreased the cost of materials and construction since the height was reduced by 80 %.

With all of this, optimizing the divergence angle is crucial to get better performance. The research results indicated that a divergence angle ranging between 2° and 5° delivers better maximum power output. A 0.7 coefficient of area ratio (COAR) with the 194.6 m chimney height could produce up to 231.7 kW (with a 364 % increment as compared to the Manzanares prototype). Integrating enhancements material such as a bell-mouth at the inlet of the chimney further increased airflow by 6–7 % and boosted the turbine power by 21 %. These modifications contribute to improving the overall performance of SCPPs while maintaining economic feasibility.

From an economic point of view, divergent chimneys plants require relatively fewer materials and hence construction costs could reduce up to 70 % as compared to the conventional ones. SCPPs can be made sustainable and affordable to generate power by analyzing their performance using optimizing tools prior to manufacturing. Hence, future research should focus on long-term performance data collection from operational solar chimney power plants, exploring hybrid systems, assessing environmental impacts, addressing scaling issues, using advanced computational fluid dynamics modeling, and exploring performance under diverse conditions.

CRediT authorship contribution statement

Hana Gebremariam Araya: Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization. **Solomon Tesfamariam Teferi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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