Comparative Assessment of Innovative Methods to Improve Solar Chimney Power Plant Efficiency

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Abstract

Utilizing Solar Chimney Power Plants (SCPPs) for manufacturing clean and environment-friendly energy has drawn a lot of attention in recent years and has (over the passing decades) become one of the most promising solutions in the solar energy field. Low efficiency, construction difficulties and other required improvements have encouraged researchers to work on this system. Many researchers put their efforts into proposing an optimized configuration for the main components, whereas others have proposed innovative ideas and add-on accessories to improve solar chimney power plants from an efficiency or construction viewpoint. This paper provides a comprehensive review of the past few decades and includes analyses of the theoretical, experimental and numerical studies conducted focused on optimizing the main characters of the system, such as the chimney, collector and Power Conversion Unit (PCU) together with other recently suggested innovative ideas and alternative technologies to improve solar chimney power plants efficiency. Concurrently, other researchers focused on hybrid solar chimney power plants to produce the desired by-product such as distilled water and so make SCPPs more practical.

Highlights

- Different types of solar chimney power plant systems are reviewed in this paper
- Various techniques toward system improvement have been categorized and discussed
- Developments in hybrid solar chimney power plant systems are reviewed
- Experimental, numerical and theoretical studies are summarized and main effective results are pinpointed
- Key important innovative ideas and strategies for improving basic components are studied alongside integrated apparatus inserting layouts

Keywords: Solar Chimney Power Plant; Renewable Energy; Solar Collector; Hybrid Solar Chimney; Accessories and Alternative Technologies.

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1. **Introduction**

At the present, with the noticeable growth in energy consumption all over the world, the limitations of energy resources, the environmental concerns associated with fossil fuels and the hazards of climate change mean that choosing a clean, accessible and abundant energy resource is fast becoming a vital necessity [1, 2]. Population growth and increasing living standards are causing an ever faster-growing energy demand. Additionally, fossil fuel depletion and Green House Gases (GHG) pollution are becoming, more than ever, a burden on the environment. Furthermore, this shortage of current energy resources and the global warming concerns has forced governments and decision-makers to shift to renewable and sustainable energy resources. Hence, in the last few decades, designing a sustainable and efficient system to produce power has, more than ever before, become an essential research issue because access to a free and sustainable source of energy is necessary for economic and social progress [3]. Considering all energy resources – fossil fuels, nuclear energy, geothermal, hydro, biomass, solar energy and other types of resources, almost all of them have some detrimental effects on the environment, but solar energy is more available, sustainable, has limitless energy potential, and more importantly, causes minimal damage to the environment. In this respect, solar chimney power plant systems (SCPPs) use solar radiation for power generation and consist of three basic components: a collector – generally a big circular and transparent roof [4], a chimney or tower, and a power conversion unit containing a turbine to convert kinetic energy into electricity. The chimney is installed in the center of the air collector and utilizes the buoyancy effect so warm air rises through the chimney once the air temperature within the 'greenhouse effect' collector has risen sufficiently [5], as shown in Fig. 1.

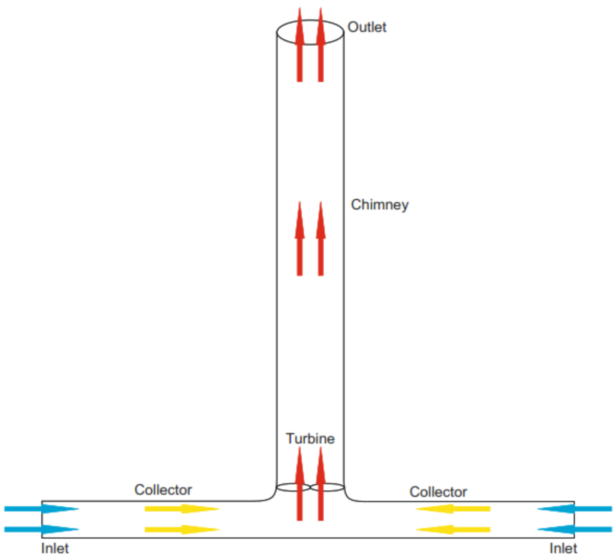


Fig. 1. Solar chimney power plant (SCPP) schematic

Multiple energy conversions take place in this form of the power plant, converting from the thermal energy of the sun into kinetic energy of flowing air and finally into electricity. Despite the simplicity of the principle, several issues exist, the foremost being their low efficiency [5]. In addition, there is the problem of intermittency (inherent of such energy sources) on rainy or cloudy days or at night [6]. Many of these obstacles have been overcome to some degree with the application of new concepts; nonetheless, there is room for significant improvement, which has kept this topic as a center for research attention. With lower construction and maintenance costs, simpler technologies, cheap and mostly locally available materials (e.g., polycarbonate for the chimney, Anti-refluxing glazed glass for collector cover, polycarbonate for turbine and copper, sand, wood and steel for other parts [7]) and little (to no) need for a high skilled specialist input (particularly full time), this energy system has become an attractive proposition for many countries [5] – particularly in remote areas and desert climates with their high solar irradiances, cheap or free land and no translation losses.

There have also been numerous published works on SCPPs due to their capability for industrial and urban applications including reviews, and numerical and experimental studies [1, 8-22]. Nonetheless, this present review introduces a more detailed, updated and comprehensive approach related to the modern developments in this technology, hoping to provide a more comprehensive insight for researchers in order to assist them in making the next generation of solar chimneys more efficient and economical. An applicable and innovative study including both experimental and analytical studies is presented in this work to cover all the recent studies performed on enhancing the efficiency of SCPP, necessary because innovation plays a pivotal role in their progress.

Moreover, because of their low efficiency, researchers have compensated for this by coupling the SCPPs with other units, which then result in hybrid plants capable of the desalination of water, generation of power, drying products, heating and ventilation etc. Hence, because in recent years, the integration of SCPPs with other units has become a focus of attention, this review also considers hybrid SCPPs to identify gaps to assist in the future investigation of such systems.

1.1 Renewable Energy and the Environment

The high rate of population growth combined with remarkable growth in developments and lifestyle standards has resulted in a rapidly increasing global energy and water demand during the last couple of decades, as shown in Fig. 2 [23]. Coupled with this is the problem that, currently, fossil fuels are the world's dominant fuel source and it is this proportion of usage (compared to other resources) which leads to excessive GHG emissions. These, in turn, exert several profound but negative influences on the environment, which promote adverse worldwide changes, such as receding glaciers, earlier plant blooming, ocean acidifications, killer heat waves, even butterflies retreating up mountainsides [24]. In addition, all nations will encounter precipitation shifts that may vary from region to region [24]. Therefore, in order to help control these impacts, it will be required to utilize alternative choices for our energy resources, such as renewable energy resources, which noticeably reduce some of the detrimental effects of GHG emissions [24, 25].

Fig. 2 represents the world energy consumption in 2019 in a million tons oil equivalent (MTOE). World energy consumption increased by about 3% in 2018. Gas had the largest increase, followed by renewable energy [23]. The same figure also shows that oil remains the world's leading fuel, making up a third of the total consumption. In 2009, all of the fuels, except oil, fell moderately. Renewable energy consumption experienced a gradual increase.

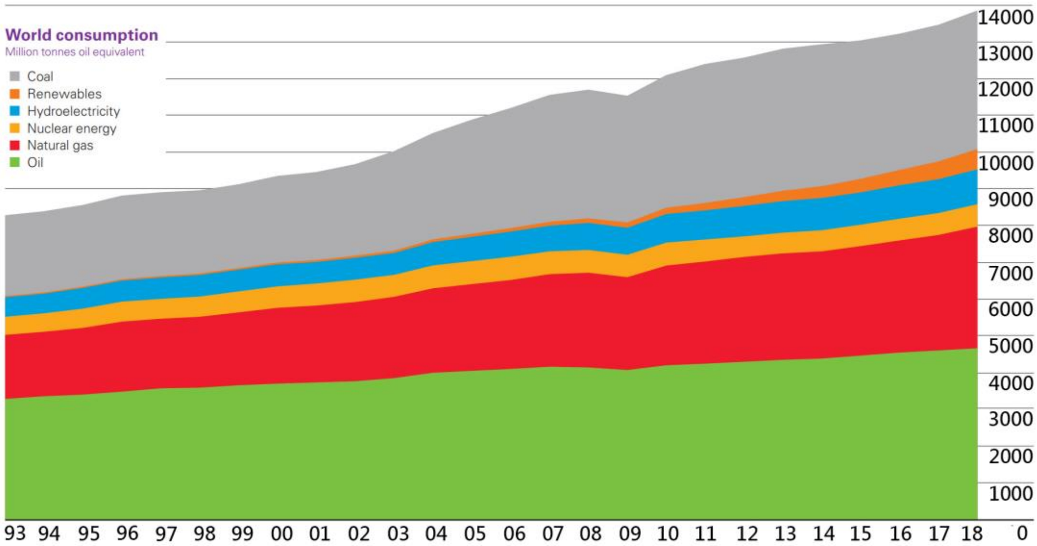


Fig. 2. World consumption in Million tones oil equivalent[23]

1.2 Solar Energy and Solar Chimney

It has been claimed that solar power could be used to reverse the damage being done by other environmentally damaging energy production methods [25] by being one of the most promising renewable energy resources and it is both clean and safe [25]. Also, rising energy prices have made governments encourage organizations and people to change to sustainable and renewable energy adoption and use, in which solar energy has been described as a widely available source to achieve this goal [26]. Even though providing incentives for energy efficiency, lowering consumer bills and public support legislations such as addressing renewable energy source subsides can accelerate renewable energy acceptance and popularity to reach energy and climate goals [27]. Amongst all of the solar power technologies (depicted in Fig. 3), PV cells play a great role within the market to supply power demands. However, they still exhibit low efficiency, high-temperature drop-off and are vulnerable to harsh winds. In addition, concentrating solar power plants are strictly dependent on direct solar irradiance, something that SCPPs can turn to their advantage because they do not depend on just radiation that comes from the direction of the sun. Another further problem of solar energy power production devices is their intermittency, but this difficulty could be handled to some extent in SCPP systems by utilizing a capability to harvest thermal energy stored in the ground and so produce a limited amount of power even at night, something not seen in the other types of solar power plant. To improve this ability, some researchers have also suggested exploiting phase change materials (PCM) – (like paraffin [28, 29] and Glauber's salt (Sodium Sulfate Decahydrate) [30] – as a latent heat energy storage medium to store more energy for nighttime power generation. PCM as a lateral thermal energy storage technology can be used in many energy systems and increase the overall efficiency besides filling the gap of demand and supply [31]. Porous materials also present exceptional properties in many applications such as thermal energy storage systems [32]. To find correlations between the effect of soil porosity and power output, Sedighi et al. [33] investigated the effect of thermal energy storage layer porosity on SCPP performance numerically. They stated that a lower porosity of the soil leads to better efficiency in SCPPs. On the other hand, Fadaei et al. [34] used an artificial neural network to examine the performance of SCPP, and Rafea et al. [30] ran an experimental setup to investigate the effect of PCM material in SCPP performance enhancement. Other investigations were performed under the influence of PCM in solar chimney power plants [35] and solar chimneys for ventilation purposes [36], as well. Even so, simpler and cheaper concepts, like filled water tubes [37], could still enhance sustained power generation and more inherently utilize the earth surface soil's ability to act as a power storage device for the system.

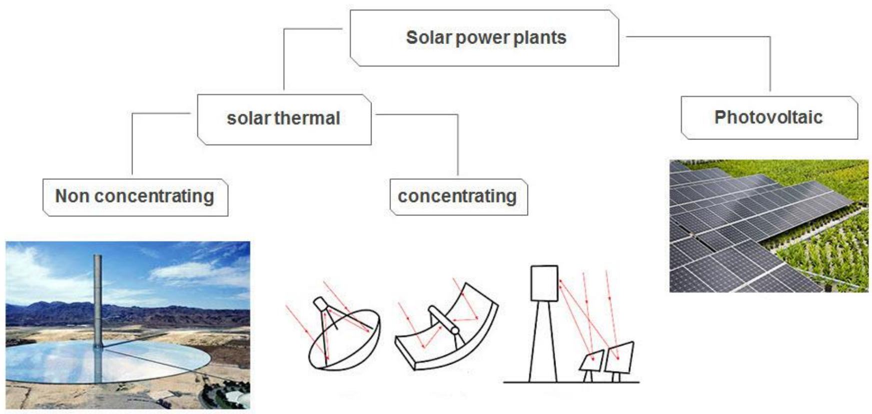


Fig. 3. Types of the solar power plant based on the working mechanism

The SCPP is a large-scale power generation unit that absorbs solar radiation and converts it into power through the installed equipment [25, 38-40]. The multiple energy conversions taking place in SCPP are solar radiation to thermal energy, thermal energy to kinetic energy, kinetic energy to mechanical energy, and mechanical energy to power, respectively [1].

The first chimney power plant was proposed by Cabanyes [41] in order to heat a house and generate electricity through an installed wind propeller, although the basic idea was not a new innovation as many years ago, Leonardo da Vinci designed a barbecue which worked using the basic idea of the updraught within a chimney [42]. However, the first actual prototype was constructed by Schlaich et al. [5] in Manzanares, Spain, in 1982, as shown in Fig. 4. Their objective was to determine the efficiency of the system [43]. The height of the constructed prototype is 194 meters, and the collector diameter, tower diameter and collector inlet heights are 244, 10 and 1.8 meters, respectively. The total weight of the prototype is approximately 125 tons. Construction of the Manzanares power plant was an inspiration to start innovative researchers in other countries to study the feasibility, in places such as China [13, 16, 44, 45], Iran [46, 47], the Mediterranean region [48], Algeria [49, 50] and other countries.

Generally, it is revealed that the amount of the produced electricity depends on the dimensions and configuration of the chimney and collector, properties of the absorbing materials and efficiencies of the power conversion unit components (mechanical turbine and electrical generator) transforming the air flow kinetic energy into electrical energy as the output power is directly proportional to the airflow velocity ($p \propto v^3$)[51].

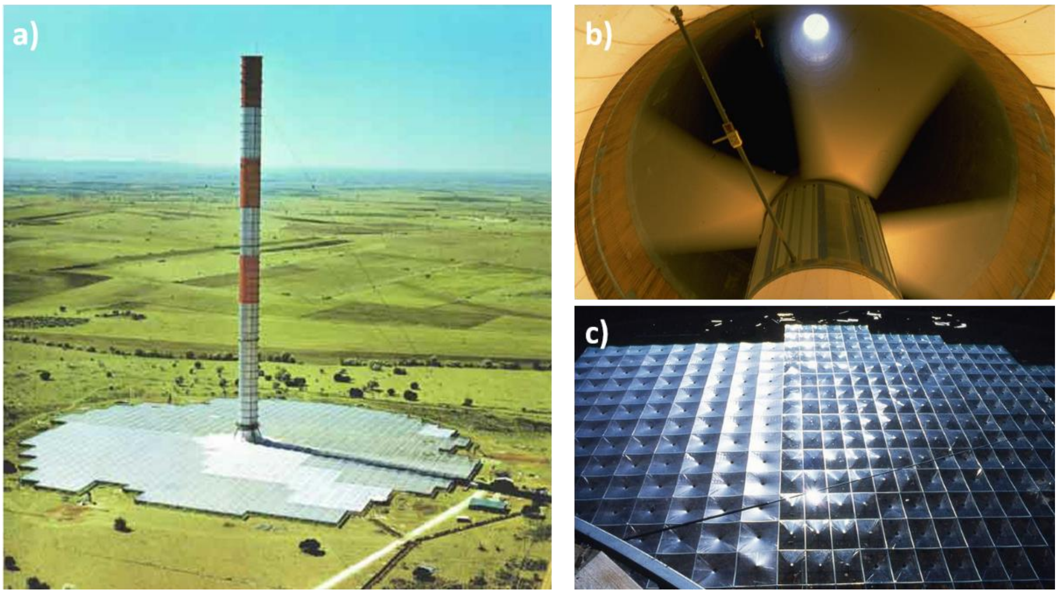


Fig. 4. Different sections of the solar chimney in Manzanares, Spain; a) side view of the SCPP, b) Turbine, c) Collector [52]

The exported results from Scopus (https://www.scopus.com/) show an increasing trend toward the solar chimney subject. The extracted data in Fig. 5a indicate a steep growth in the number of research publications on this particular issue in the last couple of decades. This dramatic growth rate in the solar chimney field represents significant interests and importance of the topic and is predicted to proceed.

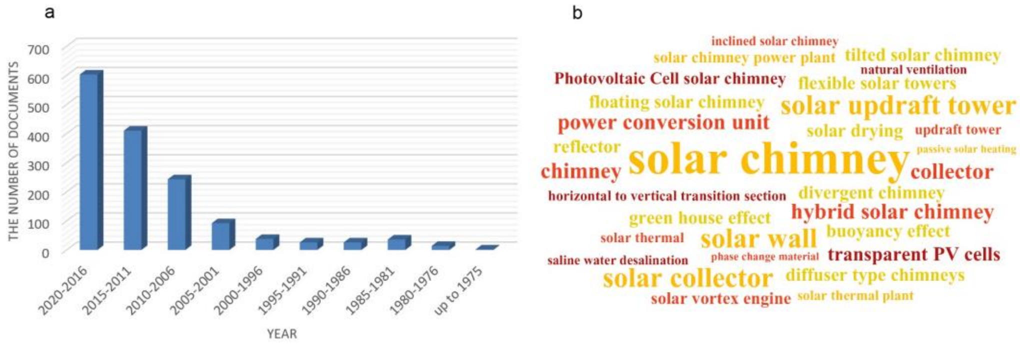


Fig. 5. (a)The number of articles per year in the field of solar chimney[53]; (b) primary keywords in the field of solar chimney

2. Basic Components of the Solar Chimney Power Plants

The SCPP (solar chimney power plant) is a system that converts both direct and non-direct irradiance into a clean, reliable and environment-friendly power. This eco-friendly system is composed of a collector – that plays a role in absorbing irradiance and heating air by the greenhouse effect phenomenon, a large chimney – that plays an important part in conducting heated air through the turbine and atmosphere, with the turbine being the final power conversion unit, as illustrated in Fig. 6. From these beginnings, there has been considerable focus on how to optimize the main components of SCPPs in order to harvest more efficient power.

The system efficiency depends on the efficiency of every major part. Thus, total efficiency is represented as follow [54]:

$$\eta_{plant} = \eta_{chimney} \cdot \eta_{collector} \cdot \eta_{turbine} \qquad (1)$$

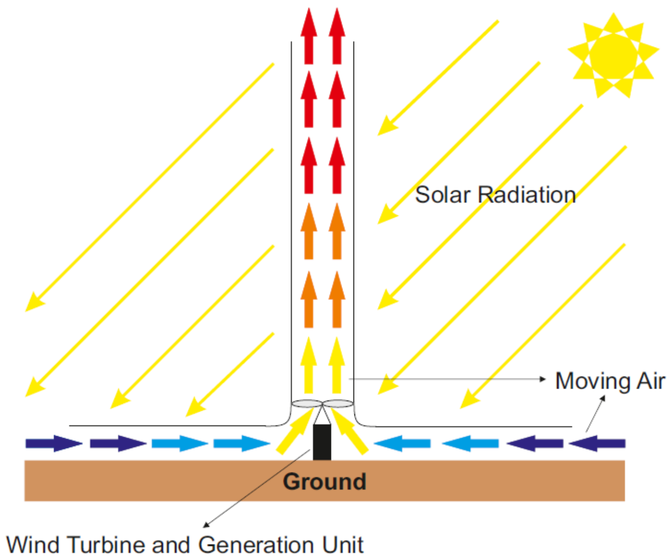


Fig. 6. Mechanism of solar chimney power generation

Many researchers have put a great effort into this area, testing experimental setups, proposing theoretical models and running numerical simulations to understand the mechanism of the system and present an optimum amount of basic parameters such as chimney height [55], chimney diameter [56], the divergence angle of the chimney [57], the ratio of height and diameter in the chimney [58], collector radius and collector inlet height [56, 58, 59], all of which have been considered as the most relevant parameters that influence SCPP's performance. As a simple precept, Schlaich et al. [60] stated that solar tower power output is proportional to the size of an imaginary cylinder that encircles the chimney inlet area and extends to the height of the chimney. However, although early studies reported that power output is directly proportional to collector area and chimney height, finding an optimum value for each parameter and the best configuration for a solar chimney remained as an argument for discussion, and there was not a complete investigation that included all of the relevant parameters. Additionally, limitations from a practical viewpoint of regional dependences and economic considerations should be considered before proposing an optimal efficient SCPP design.

2.1 Chimney

The part of the system that conducts heated air from the collector part to the atmosphere, utilizing the buoyancy effect caused by inside and outside of apparatus temperature differences, has been called a chimney, updraft tower or solar tower. In respective of the term, it is a giant tube that is sited at the center of the collector, acting as the thermal engine for the plant. Despite the long tube, it has been claimed that the chimney has a low friction loss because of its suitable surface-to-volume ratios and is so likened to a hydropower station pressure tube or penstock [60].
Chimney efficiency is given by the following equation and depends on height in a particular case [25].

$$\eta_{chimney} = \frac{g.H}{c_p.T_0} \qquad (2)$$

$\eta_{chimney}$ is the efficiency of the chimney where g, H, c_p and T_0 correspond to gravitational constant, height of the chimney, specific heat constant and outside temperature at ground level.
Using the Boussinesq approximations, the speed reached by free convection can be calculated. Indeed, for a chimney with a height of about 1km, deviation from the exact solution given by the Boussinesq approximation is negligible and the error is trivial [61].
Even though it is reported that the output power grows with the square of the chimney height [56] as a result of the increased mass flow rate, approval for a large chimney height is not always available, so this claim has yet to be fully verified. In addition to the effect of the chimney height on the total efficiency, there are still constructional limitations and other natural hazards that should be taken into consideration, which are inevitable when making such a large chimney. Moreover, aerothermal characteristics of flow, inside and over different chimney shapes, can

strongly affect power output. Backflow concerns should also be considered in the presence of the crosswinds.

Nonetheless, many configurations have been proposed to cope with this issue, although a large chimney is still vulnerable to a harsh wind storm and other natural forces like seismic activities [62], especially with super-tall chimneys and for non-urban areas [63-65]. Wang and Fan summarized 739 types of high chimney failure cases and compared effective factors in observed failures in a complete review [66]. Schlaich [67] considered the danger of buckling as the reason for the height limitation of natural draught cooling towers which was about 200 m. He suggested stiffening spoked wheels as a countermeasure.

Many layouts have been proposed in respect of structural choices to deal with possible structural failure, but the best options of material still proved to be reinforcement concrete, guyed tubes made from corrugated metal sheet, and cable-net designs with cladding or membranes, which is an appropriate choice for less developed countries [60, 68, 69]. Constructional consideration for the chimney wall thickness would also suggest decreasing wall thickness from about 1 m just above the support on radial walls to 30 cm halfway up, which then remains constant all the way to the top, stiffened at several levels with cables arranged like spoked wheels within the tower to counteract over-toppling caused by wind suction in flanks and the use of these thinner walls [69]. Structural configurations are illustrated in Fig. 7.

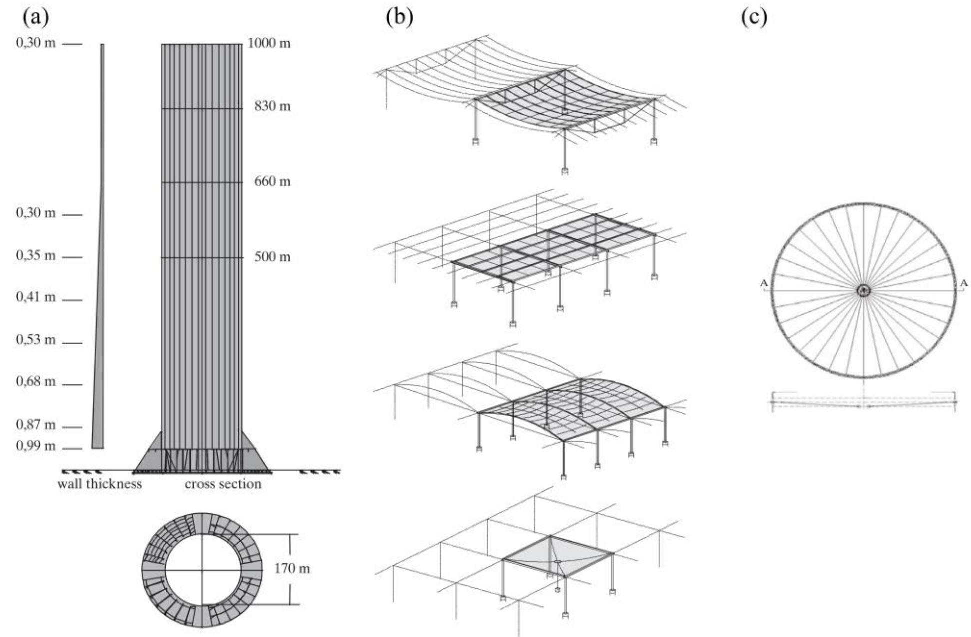


Fig. 7.Structural configurations:(a)Wall thickness variation of a 1000 m height and 170 m diameter tower;(b)Collector design options; and(c)Spoked wheels, the spokes are made of vertical steel slats [69]

Another limiting factor in an increased chimney height is the fall in raised air temperature due to heat loss and its decreased velocity due to flow loss, with subsequent reduction in buoyancy. Accordingly, the greater flow loss and lower buoyancy effects in longer chimneys, limits chimney height for optimized power output. As demonstrated by Zhou et al. [55] for the first time, they emphasized that there is a maximum height for the chimney, and this height changes with the collector radius. To overcome this limitation, researchers then started looking at other parameters to optimize [70]. For example, it was shown that an increase in the collector area could compensate for the lack of chimney height [60]. Cottam et al. [56] suggested a linear relationship between power output and collector radius the same as the chimney radius. Schlaich [67] claimed the same output might result from a large chimney with a small collector roof area and vice versa – although this is not strictly a linear correlation (between power output and collector area times tower height) because of collector friction losses [60] – and he also implied there is no optimum physical size for solar Chimneys. Additionally, to decide the optimum dimensions the specific construction costs of each item must be known.

From a building cost viewpoint, Wolfgang Schiel suggested that operating a large chimney is much cheaper than operating many small ones [68] even though Cottam [56] prefer several smaller collectors with a size of 3000m over a very large one.

Zhou and Xu [71] estimated the chimney and collector costs. The chimney cost is calculated to vary from €175.4 to €416 per superficial area of a cylindrical chimney, and the collector price is estimated to vary from €7.27 to €34.22 per collector area. The calculated costs depend on the physical size of the solar chimney, construction time, construction size and so on.

More recently, other investigations aimed at coping with chimney design challenges have been undertaken, but the discussion still continues. For example, to evaluate the effect of diameter, a chimney 'slenderness' ratio parameter has been defined, which is the ratio of chimney height to chimney diameter. Normally slenderness ratio could vary from 5 to 12, influenced by various parameters. However, Petrorius [72] reported optimal slenderness of 5-6, considering the risk of cold air inflow. There is also a critical value of 6-8, and it is claimed that the diameter has a prominent effect under this value [73]. Considering the influence of winds, Kashiwa [74] suggested the slenderness ratio of 12 and mentioned that wind variation could have a great influence on the updraft.

2.2 Collector

One of the major components of the SCPP, the collector, plays the role of a heat exchanger within the system, in that the collector converts solar radiation into thermal energy utilizing the greenhouse effect. The thermal energy of a heat absorber first warms the air and then the thermal energy of this heated air is converted to kinetic energy due to its buoyancy effect. A transparent roof, column structure and support matrix are all of the primary parts of the collector, and the principal mechanism occurs when irradiance through the transparent canopy hits the absorber section. The transparent canopy, which is often plastic or glass, is then not able to pass any infrared radiation emitted from the absorber back to the atmosphere, but instead, the absorber heats air which is then exploited by the overall process. Although, as has been mentioned, that output power is directly proportional to the collector radius, similar to chimney height, the collector area is limited. Guo et al. reported a maximum collector area for the Spanish prototype through a MATLAB program calculation [59]. Collector inlet height, collector inclined angle and collector profile shape are the major parameters of this study. Despite the great efforts from many researchers, the issues governing an optimal collector by taking all parameters into account remain, at this time, still unsolved – the same as with the chimney. Because optimal dimensions must include economic factors, many researchers have pragmatically employed a multi-objective optimization approach [75, 76], from which various researchers have proposed alternative ideas to improve collector efficiency and for harvesting more power.

Collector efficiency can be shown as follow [77]:

$$\eta_{collector} = \alpha - \frac{\beta . \Delta T_0}{G} \qquad (2)$$

This equation shows how collector depends on collector heat loss G, collector effective absorption coefficient α , collector heat loss coefficient β and airflow temperature rise inside the collector ΔT_0.

2.3 PCU

The Power Conversion Unit (PCU) consists of one (or more) turbo-generator(s) (turbine coupled with generator), the output from which depends on the air mass flow rate being fed to it from a horizontal to vertical transition section (HTVTS) between the collector and the chimney. With some designs, inlet vanes have been used to redirect and guide the flow through the turbine, but the PCU may also include a diffuser located behind the turbine for the single turbine configuration. Bernardes et al. [78] presented a series of possible configurations for the HTVTS based on three basic geometric configurations which are given in Fig. 8 and simulating thermodynamic behavior using natural laminar convection. The concern in the power conversion unit is the recirculation of air flow caused by unsuitable configuration choices. Bernardes also stated that mass flow rates for rising air are greater for a conic SCPP. Indeed, there must be considered that straight junctions induced the lowest mass flows due to flow recirculation. Later Muller [79] pointed to a 43 percent loss in multiple horizontal axes with guiding cones.

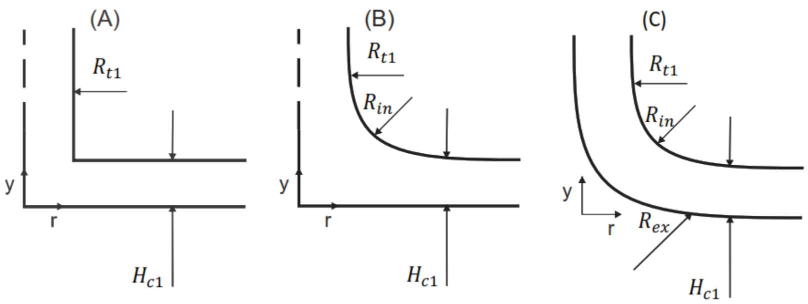


Fig. 8.Structural configurations of horizontal to vertical transition section (HTVTS) [78].

With respect to the siting of the turbine, some layouts have been proposed. Pasumarthi and Sherif [80] suggested installation at the top of SCPP, whereas in most literature, turbines are located in the base because of installation and maintenance difficulties, especially for super large SCPPs. Bonnelle [81] observed a relatively negative pressure in SC for in-base installation and relatively positive pressure for in-top installation, explained by the fact that static pressure must drop from upstream to downstream. Furthermore, many arrangements have been proposed for the actual turbine configuration – a single vertical axis, multiple vertical axes and multiple horizontal axes that could contain inlet guide vanes (IGVs) or not (all as shown in Fig. 9). Schwarz and Knauss [82] designed a single vertical axis for SC, and Gannon and von Backstrom [83] utilized supporting structures for IGVs. Bilgen [84] suggested one pair of counter-rotating rotors as an alternative turbine layout. In fact, the proper choice depends on the solar chimney size. In small solar chimneys, multiple turbines may not be a good selection, whereas for very large systems, this could reduce manufacturing costs and maintenance challenges. In the power conversion unit junction, the shape of the collector in the chimney also has a significant effect on the thermo-hydrodynamic field quality. Chergui et al. [85] investigated different junction shapes and their resultant junction with the diffuser had a higher mass flow rate in comparison to the curved junction and the straight junction.

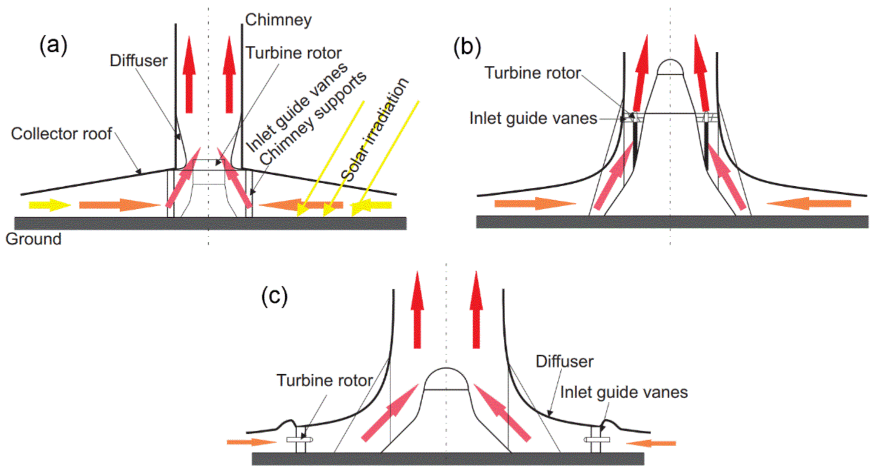


Fig. 9. Configuration of turbine installation: (a) single vertical axis; (b)multiple vertical axis and; (c)multiple horizontal axis [1]

Ayadi et al. [86, 87] also investigated the effect of the turbine diameter and number of blades and reported that turbines with the largest diameter and the lowest number of blades are the best option for small-scale SCPPs. Kasaeian [88] conducted a 3D simulation of large-scale SCPP considering turbine blades. However, contrary to Ayadi's experimental setup, Kasaeian reported that a turbine with five blades presents more power output than that with three blades, whilst 3-bladed turbines provided a higher mass flow rate. More research is needed in this subject to determine an optimal turbine configuration.

3. Innovative Ideas and Alternative Strategies

Despite the clean and eco-friendly energy production from SCPP systems, their disadvantages of noticeably low efficiency and high construction costs have presented significant challenges to their successful commercialization. To reduce these problems, researchers have focused on finding the optimized new configurations and novel alternative ways to improve SCPPs efficiency. Optimizing major parameters, studying different configurations, utilizing different mechanisms such as thermal fins or accessories like intensifiers, and combining these improvements with alternative systems such as water desalination – have been widely studied with the aim of improving system performance and providing a reasonably efficient, robust, feasible and economic system.

3.1 Different Geometry Configuration

To deal with the low efficiency, the first and simplest option is to optimize the major components and make changes in their basic configuration. This is simple and incurs lower costs in comparison to integrating systems or involving different components. Numerous researchers have focused on applying different configurations and optimizing related parameters in an effort to improve SCPP efficiency.

3.1.1 Chimney

One focus has been an investigation of different chimney configurations, and this includes changing the cylindrical shape of the chimney or presenting novel layouts. Ming et al. [89] studied the effect of divergent and convergent chimney angle and chimney height to allow a better understanding of different shape parameters. They compared results obtained against a reference case including a cylindrical chimney shape. With the divergent type of chimney, the diameter increases slightly with height, and this affects the low static pressure at the chimney inlet and consequently has a significant effect on the air velocity value, which promotes greater airflow inside the system. Nsaif et al. [90] suggested an optimum amount for both chimney height and diameter, although by increasing these amounts, the performance increases and chimney diameter was found to have the maximum impact. Okada [91] et al. suggested a diffuser-type chimney to increase the power generation in the system. The result of their CFD analysis in large-scale plants revealed that a focused airflow in the throat increased power generation and the flow speed throughout the chimney, but especially at the bottom – a precept which was further studied on an indoor scale solar chimney. They concluded that a divergence angle of 4 degrees increased the power output by about three times that of a straight chimney. Jameei et al. [92] assessed 15 types of chimney walls based on a three-step procedure from a convergent-divergent form to circular, concave-convex and parabolic curves. The results showed about a 50 percent increase in velocity for the parabolic curve. Koonsrisuk et al. [93] investigated both the effects of collector slope and chimney convergence and divergence angle. A similar study was performed by Nsaif et al.[90] and adiverging and converging-diverging chimneys showed improved power output compared to the standard chimney. Patel et al. [94] also performed a series of twelve case studies to investigate the effect of chimney divergent angle and collector height. Ohya et al. [95] performed an indoor laboratory experiment analysis and showed that power output for diffuser-type towers can be increased by 4 to 5 times in comparison to conventional towers, but also showed a dependence on air temperature increments inside the collector. Nasraoui et al. [96] found that the chimney divergence angle has an optimum value depending on chimney height. Their findings revealed that the optimum divergence angle to solar chimney scale relationship is nonlinear, and that the value of the divergence angle decreases by increasing the solar scale and hence for commercial SCPPs the optimum divergence angle would be the more suitable choice.

Hu et al. (Fig. 10 [97]) carried out several case simulations to discover the best shape for the diffuser-type chimneys, and they reported that diffuser-type chimneys could handle more than 13 times the power output than that of simple cylindrical solar chimneys. They showed different parameters of AR (area ratio) and H_d/R_{in} (where H_d is divergent section and R_{in} contributes to the start of the divergent section) could affect the aerodynamic characteristics of flow inside the chimney and expansion loss, both of which directly affected performance. Comparing simulation results revealed that a divergent solar chimney configuration which has the largest H_d/R_{in} is the best option for power generation, the DISC is second-best option and the DOSC is the last. They also proposed a controlled approach for the design of a solar chimney containing a variable diffuser outlet. The concept was that the user could change the area of the outlet and so adjust the fluctuating power output.

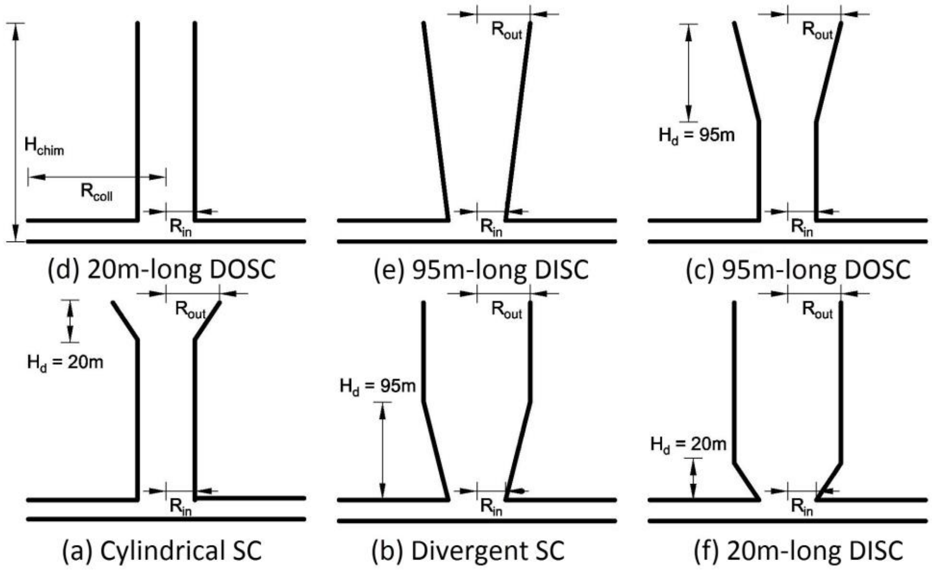


Fig. 10. Examination of different diffuser types carried out by Hu[97].

Hu et al. [98] studied a wide range of AR changes of the tower from 1 to 32 and emphasized that power output improvement is dependent on chimney height. However, the situation is not that simple. Divergent chimneys can act as a diffuser, and this has a concerning impact on flow characteristics. The formation of the large eddies near the wall in a diffuser represents the onset of stall phenomena, which could then lead to flow blockage and unwanted backflow. In the Xu Zhou et al. [99] investigation, with a small outlet-to-inlet AR cases, the flow goes up normally without any backflow, but the stall phenomena were observed for outlet to inlet ARs larger than 11.9. For even larger divergence angles, backflow occurs over a larger proportion of the flow area and boundary layer separation occurs lower down within the chimney (see Fig. 11c, d). This backflow brings ambient air into the chimney, which then reduces the average temperature and leads to a large reduction in buoyancy and pressure potential. Further chimney configurations, such as convergent chimneys and opposing (convergent-divergent chimney) designs have been examined by Bouabidi et al. [100]. Their results showed that the air velocity values are affected differently by each configuration. For example, the divergent chimney revealed the best results in this study, whereas the convergent configuration degraded maximum velocity, and the opposing chimney only enhanced the velocity compared to the standard case. Das et al. [101] found that the velocity of air inside a 7m height chimney was enhanced by 59.4% in a 2° divergent chimney as an optimum design for 1° to 5° divergent angle study. At the same time, divergent angle introduced as optimum for a 5m height chimney, Boudabidi et al.[100] reported a 45.8% increase in air velocity. Chimney divergence and convergence investigations are summarized in Table 1.

Table 1. Chimney divergence and convergence investigations

Investigated divergence and convergence angle† (DA), (CA) and area ratio (AR)	Optimal range	Chimney height(m)	Power output‡ normalized by the power of reference case (AR=1 OR DA=0)	ref
AR (div):1.56,2.25 AR (con):0.25,0.56	-	800	AR (div):1.06,1.07 AR (con):0.8,0.95	Ming [89]
AR (div):1,2,4,8,16,32 AR (con):0.25,0.5,0.75	AR (div):16	100	AR (div):1,4.27,18.49,69.07, 179.16,120 AR (con):0.02,0.09,0.19	Koonsrisuk et al. [93]
DA:1,2,3	2	10	7,10,9.8	Patel et al. [94]
AR (div):3.09,12.39,49.56	12.39	10	7.9,13.6,11.2W (absolute power)	Vieira et al. [102]
DA:4	-	0.4	3	Okada [91]
DA:2.4,4,7 CA:4,7	DA:2.4	-	DA:4.2,3.9,2.8 CA:0.8,0.4	Chergui [85]
DA:0,2,4 and 6	4	2	11.8,31.93,52.5, 46.74 mW.(absolute power)	Ohyaet al. [95]
AR (div):1,4,10,22,32	10	200	1,8.5,13.5,10,6.6	Hu et al. [98]
AR (div):3.94,8.76,11.83	8.76	194.6	7.58,11.9,7.2	Xu et al. [99]
DA:0,1,2,3	1	195	34,70,64,49 kw (absolute power)	Aakash Hassan et al. [103]
AR (div):4,6,8,10,12	10	195	440,604,678,702,695kw (absolute power)	Hu et al. [97]
AR (div):4,9,16,25,36 AR (con):0.25	AR (div):16	12.3	AR (div):15.3,24.3,26.1,19.5 ,15.3 AR (con):0.2	Lebbi et al. [104]
DA:2,3,6,9	3	100	66,69.3,61,44.5	Nasraoui et al. [96]
DA:1,2,3,4,5	2	7	0.63,1.07,1.04,0.95,0.86 (W power)	Das et al. [105]

Other researchers have investigated different practical configurations for the updraft tower by manipulating the chimney profile. Nasraoui et al. [106, 107] proposed a

† degree
‡ The extracted values from diagrams and tables and in case of velocity report values obtained from turbine model power output $P = 0.5.\rho.A.u^3$

hyperbolic-shaped profile for the chimney and the results suggested an enhanced power output in most cases. As before, the power rise suggests an optimum range, but these are more effective for larger outlet to inlet diameter ratios, showing almost constant chimney efficiency changes with very large diameter ratio, whilst with the conical section, degradation was higher in large values. In comparison with conventional conical chimneys, the hyperbolic chimney showed a 45 percent enhancement with a diameter ratio of 8. This is because a conical chimney increases power by 250 percent compared with a straight chimney with the same diameter ratio. The conclusion is that a diverging chimney with different shapes might then form a key parameter in enhancing the performance of SCPPs and so present an attractive solution for low-efficiency SCPPs.

A further idea of utilizing air flowing into a low static region was suggested by Okada et al. [91, 108]. They suggested utilizing a 'brim' that acts as a vortex generator and so provides a low-pressure region in the chimney outlet, and this idea, exploited in the wind-lens, has resulted in a two- to three-fold increase in power output [109]. Singh et al. [110] suggested that a bell-mouth shape of the collector entrance can provide a good uniform static pressure in the chimney and can handle the flow susceptible to recirculation in the outlet. By examining divergent and convergent chimneys and wedge-shaped collectors, Singh claimed that an optimized chimney results in 110 percent higher velocity, and with optimized chimney and collector together, this amount can climb to 240 percent.

Kebabsa et al. [111] proposed a novel tower solar chimney concept to alleviate the potential problem of boundary layer separation in large divergent angles and corresponding performance degradations. The so-called annular tower solar chimney power plant chimney comprises of two walls of which one is inside the chimney, and the other is outside and which guides the flow in between (see Fig. 11a), and can improve power output by 32% at its best (17m exterior tower radius and 13m interior tower radius). This layout decreased the size of the recirculation area and prevented eddy generations which are responsible for power degradation. The annular tower solar chimney power plant is claimed to benefit from pressure recovery due to the chimney diffuser shape and can prevent the adverse effect of the possible stall. Kebabsa et al. also proposed a shorter inner wall at the outlet, which compromises the efficiency but reduces the second wall construction costs considerably (Fig. 11b). The alternative concept has an adequate height of 5m to cover the eddy generation area in a 185m chimney and is known to be a good choice by cutting the construction costs up to 40%, only with a 6% power loss.

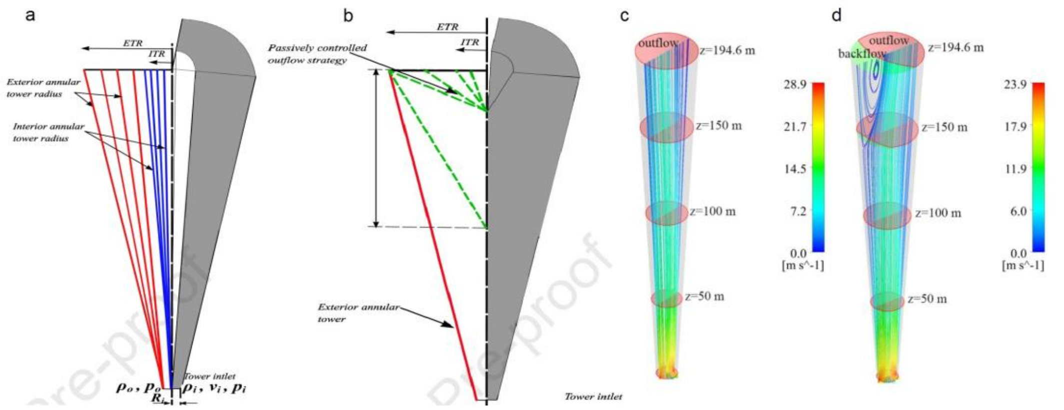


Fig. 11.Schematic of a) annular tower solar chimney power plant; b) annular tower solar chimney power plant with passively controlled outflow[111]; Streamlines of the divergent chimney for different chimney outlet-to-inlet area ratio of c) 8.7; d) 11.9 and backflow [99]

3.1.2 Collector

The collector is the second major component of SCPPs and has a significant effect on the performance of the system. Early researchers have therefore investigated the impact of major collector parameters in order to reach a better understanding of the effect of these parameters [112]. Whilst the dimensions of the collector radius and the chimney height are considered as primary factors that directly affect power output, many investigations have suggested that collector radius can have a greater significance on performance, and consequently, any increase in chimney size is more effective with large diameter collectors [113, 114]. Ming et al. [89] studied the effect of the collector height in addition to the collector radius for a better understanding of the different shape parameters. Although decreasing the collector height led to an increased power output, collector height showed to be less important compared to the other major parameters such as chimney height, collector radius and chimney diameter [102, 113]. Patel et al. [94] stated there is an optimum value for the inlet opening height and that, in fact, a very low inlet opening height could end up reducing the power output because of a lower mass flow rate. The same results were obtained by Daimallah et al. [115]. Varying collector height caused a better mass flow rate and then decreased after reaching a certain point. For collector radius, also mass flow rate increased and then stabilized. Thus, a big collector beyond the maximum value was not considered effective based on increase in investment cost.

Ordinary flat collectors cause pressure drop due to a cross-sectional restriction of the flow near the chimney, but sloped collectors are a promising solution. Hence the slope of the collector could play an important role related to the quality of hydrodynamic flow inside the chimney, the same as chimney divergence and convergence angle as discussed earlier (Fig. 12). Ayadi et al. [116] studied a solar chimney with the combination of convergent collector output and divergent chimney bottom and showed that generated power could rise by 32%, which is promising for designers.

Hakim Semai et al. [117] reported an entropy reduction in converging SCPP. Sun et al. [118] also investigated the effect of the inclined angle vs. power output and other flow characteristics for the collector. They observed vortices appearing and increasing inside the collector, especially near the chimney position, with positive inclination angles (β). Aakash Hassan [103] and Ayadi [119] also studied the effect of the collector slope and reported that a negative inclination angle leads to a higher velocity and hence a higher power output as a result. Ayadi suggested a 125 percent increase in velocity for a variation of 2.5 degrees in inclination angle. Aakash also suggested that increasing the inclination angle could result in a higher mass flow rate and larger air velocity. Although very large angles – about 6 degrees – could lead to air recirculation within the collector due to a density gradient and hence causing air blockages a result.

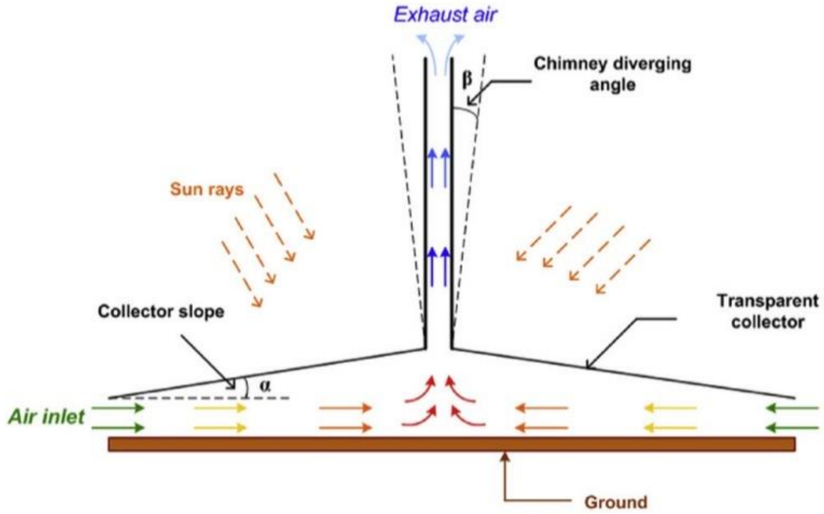


Fig. 12. Chimney diverging angle α and collector inclined angle β [103]

Patel et al. [94] investigated the influence of both collector outlet height and collector outlet diameter. Their results for the collector output height correlates well with other investigations and indicates that a large collector output height could limit growth in power output. They also observed a strong effect regarding the collector outlet diameter and claimed that with a large value of collector outlet diameter, a larger quantity of air is able to enter the chimney with a reduced flow resistance producing greater power. Kebabsa et al. [120] investigated different collector entrance configuration parameters, including sloping distance and angle. They reported even better results in comparison to normally inclined collectors, with up to 13 percent more power output than a conventional inclined collector. Cottam et al. (Fig. 13 [121]) investigated a series of canopy profiles for the optimal canopy layout and power output.

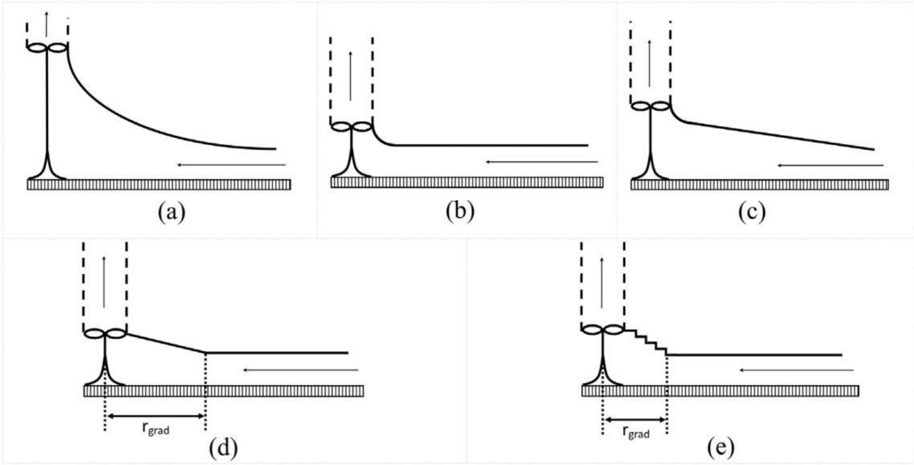


Fig. 13.Collector profiles: (a) exponential; (b) flat; (c) constant-gradient sloped; (d) segmented; and (e) segmented & stepped [121]

They compared the results for an exponential profile, a flat profile, a segmented profile, and a segmented with stepped profile, and reported that collector outlet height is an important parameter and could help control the pressure drop in the collector to chimney transition section. The adequacy of the cross-sectional area in the transition section is a known determinative parameter for pressure loss. And even though an exponential profile has proved to be the best choice, Cottam et al. showed that a segmented collector profile could almost reach the performance of an exponential profile, but with a simpler design and lower cost. They also suggested a stepped segmented profile for good power output to construction cost balance.

3.2 Accessories and Integrated Apparatus (Auxiliary Techniques)

Many researchers have tried adding accessories to help improve the performance of SCPP systems; for example, supplementary apertures aim to enhance either the heat transfer or the flow field inside the solar chimney. Relating to this, Hosseini et al. [122] performed a numerical simulation to study the effects of longitudinal rectangular fins on solar chimneys, both in continuous and discontinuous fins. Comparing these to a flat absorber, Hosseini declared that, with appropriate interruption gaps, discontinuous fins could enhance the performance of solar chimneys over and above that produced from continuous fins. They also showed that despite the dependence of efficiency on absorber area, the efficiency could still be improved by increasing the depth ratio of fins because of the heat transfer area, and hence the net heat transferred to the airflow will be increased as a result. They also noted that disturbance and reformation of the boundary layer could lead to an improvement in the heat transfer coefficient but in the appropriate gap due to the effect of declining in the absorber area. They also reported that increasing the number of fins would improve thermal performance. Hosseini et al. [123] also compared different shapes of fin, such as triangular, elliptical and rectangular in natural convection solar air heaters and declared that the thermal efficiency of a solar air heater with rectangular fins is 5.5% higher than those containing elliptical and triangular fins.

Following a different approach, Shabahang Nia and Ghazikhani [124] studied the effect of passive flow control devices on solar chimneys. They implemented different obstacle shapes such as half-circle, rectangular and triangular obstacle shapes to alter the flow field and so improve inflow mixing using secondary flows and vortex generation. They also considered boundary layer agitation and fluid mixing as a contributor to enhancing the Nusselt number. The study observed improvements in all cases, but an obstacle with a triangular profile produced greater thermal performance enhancement because the flow pattern was not blocked but rather was guided toward the chimney. Their passive control resulted in an increasing velocity rate and consequent energy output improvement of up to 41.2%.

Moreover, Fallah et al. [125] evaluated the effect of artificial roughness on the ground as the air passes through the collector. They considered an optimal location for this artificial roughness, which reduces air velocity but improves heat transfer compared to collector without roughness. Hence, either from natural roughness (like the ground surface) or from the artificial roughness of a form of an energy storage system, roughness has proved to make a valuable impact on solar chimney system performance. That being said, it has been suggested that installing artificial roughness near the collector entrance has no significant impact. So, to cope with the difficulty and limitations of a large installation field and higher collector efficiency, many researchers have applied different configurations and technologies to resolve this problem. In a similar study, Ayadi et al. [126] investigated the impact of placing obstacles on the airflow distribution inside the collector. The findings showed 11.5% and 14.75% more power generation in one and two obstacle placements at the collector output, respectively.

Pretorius (Fig. 14)[72] introduced a secondary roof integrated with an airflow regulation mechanism. In the Pretorius concept, the bottom section remains closed when less power is needed, and the system is in the ground energy-storing mode. At other times, the bottom section is opened, and flowing air captures the energy previously stored within the ground.

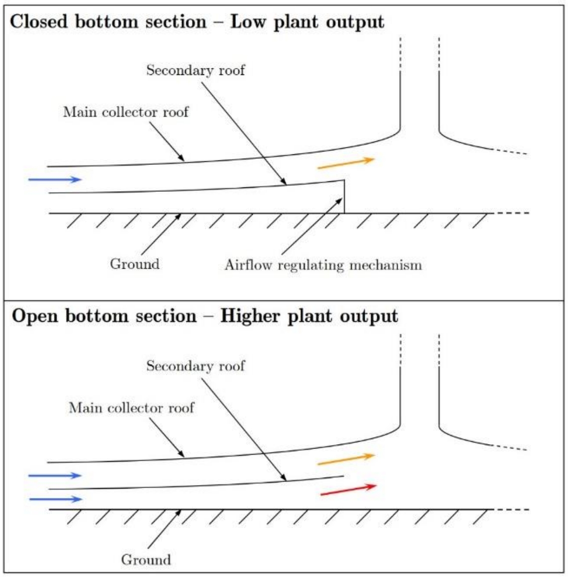


Fig. 14.A secondary roof collector by Pretorius [72]

Nasraoui et al. (Fig. 15) [127] suggested a novel collector design utilizing two flow paths. They developed a comparison between (a) standard configuration, (b) parallel in-flow channels and (c) counter in-flow channels. The results show greater improvement for the counter-flow case, but improvements occur in both cases with parallel and counter-flow configurations to maximum velocity and temperature rise.

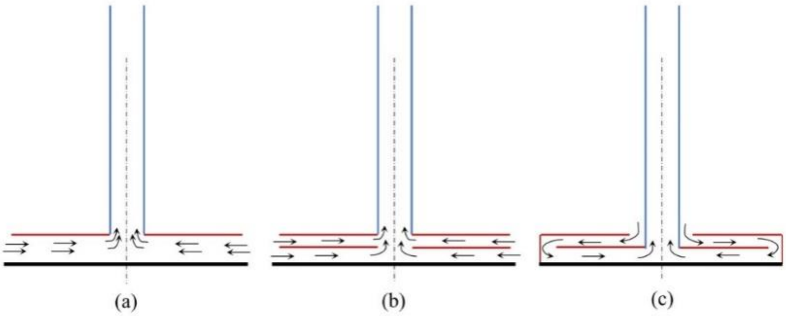


Fig. 15. Different configuration of novel collector design (a) standard collector; (b) double roofs collector with the parallel flow; (c)double roofs collector with counter flow [127]

Nasraoui et al. [128] predicted the effect of the concavity in the collector by defining the function of the concavity ratio as the curvature radius of concavity in the collector roof divided by collector radius. They proposed that a concave collector could enhance the performance of the system and produce more power by increasing the concavity ratio of the collector, by which, the velocity inside the collector is increased (Fig. 16a).

Mehdipour et al. [129] claimed that the poor performance of the solar chimney can be justified by the presence of the secondary flow underneath the collector and considered the collector angle as the most critical parameter for controlling the formation of secondary flows. They also classified the secondary flows into two categories: rotational flow between canopy and collector and reverse flows toward the collector inlet and also showed the best performance was observed in divergent collectors while the worst performance occurs in convergent geometry.

They also suggested that increasing the collector radius doesn't seem to be a good option due to the reduction of its thermal performance and increase in construction cost, which was contrary to the previous researches. They claimed that although an increase in collector area increases power, it is not a desirable option. The effects of canopy angle on the secondary flows can be observed in Fig. 16b. It can be observed that contrary to the convergent collectors, formed vortices in the divergent form are sucked more readily through the chimney.

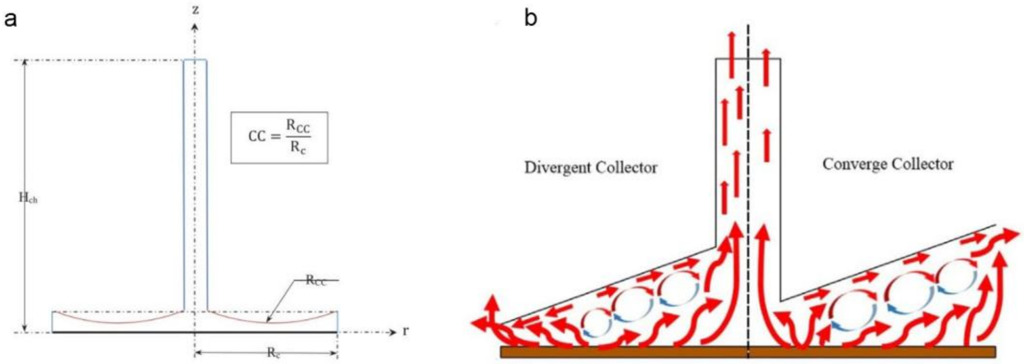


Fig. 16. (a)Concavity ratio of a collector [128]; (b)motion of secondary flows in convergent and divergent chimney [129]

Since the bigger collectors do not necessarily improve the overall performance due to the thermal performance degradation and added costs [129], improving the thermal performance by adding reflectors can be an excellent alternative that enhances the solar chimney plants significantly.

Rezaei Shahreza and Imani [130] carried out a novel investigation on a small-scale solar chimney setup utilizing intensifiers to increase heat flux on the collector and hence increase incoming irradiance. The layout is depicted in Fig. 17a. They also located an air tank underneath the chimney to increase the absorption of solar radiation reflected by the intensifiers. In addition, a mechanical assembly was designed to allow the mirrors to traverse the orbital path in order to track all-day sun movement. They showed that, by using this apparatus, air velocity within the chimney could be increased, and this leads to greater power output. They recorded a maximum air velocity of 5.12 m/s – which was remarkable for this test plant size – showing an approximately twofold increase compared to a without-intensifier prototype [131].

Faisal Hussain et al. [132] formulated an exergy and energy balance equation for the SCPP and observed maximum exergy destruction, and consequently, the highest improvement potential which happens at the floor. They, therefore, proposed a new design of a solar chimney with enhanced incident solar radiation aided with reflectors depicted in Fig. 17b. As a result, the efficiency gain was up to 22 percent compared to a conventional solar chimney, resulting from an almost ten percent increase in floor temperature.

Aliaga et al. [133] also modified solar chimneys by placing a heat exchanger inside the chimney to replace the collector (Fig. 17c). Aliaga claimed heat exchanger integrated chimneys can achieve higher densities in comparison to conventional prototypes of the same height. This design also can be used as a perfect option in areas with limited or expensive land prices.

Khidhir and Atrooshi [134] also redesigned their experimental solar chimney power plant by adding a tracking reflector and reported a 22.22% airflow velocity improvement. In Khidhir's modified solar chimney power plant collector includes one-third of the conventional collector area and reduced size is counted to solve constraints in restricted land areas. Adding reflectors was considered to be a good alternative option to recover reduced collector area according to the considerable velocity increases.

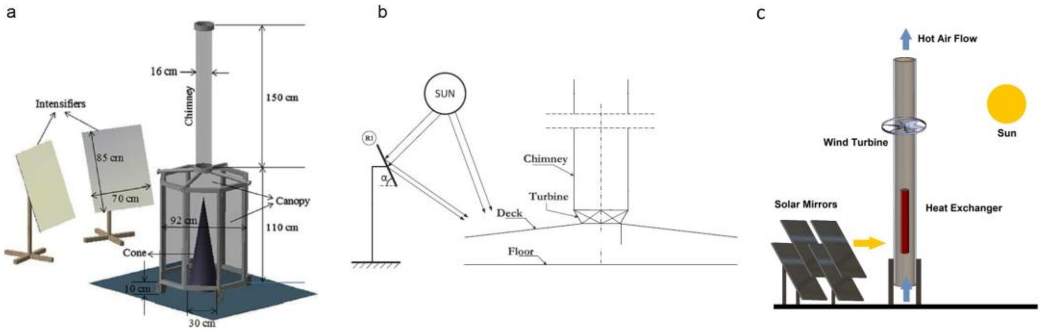


Fig. 17.A schematic of SCPP setup aided with reflectors (a) Rezaei and Imani[130]; (b) Hussain and Al-Sulaiman[132]; (c) integrated heat exchanger and reflector SCPP proposed by Aliaga et al [133]

Many authorities have reported that the main obstacle for designing very tall chimneys is that which is caused by the crosswind forces, and this induces transversal stresses to the construction, which needs to be resolved before successful commercializing. Furthermore, the cost of erecting such super tall towers by traditional construction methods was one of the main drawbacks which held these systems back from the beginning up to the present time. The design considerations have therefore caused a lot of difficulties for such rigid tall structures and produced many patent applications to cope with the problem. One such innovative configuration for a tall chimney has been proposed by Papageorgiou [135-142] (Fig. 18). In which, in order to reduce the chimney construction costs and resolve the difficulties, he utilized the merits of the airlifting force from an inflated fabric structure instead of a heavy rigid concrete body. The floating solar chimney (FSC) design, therefore, consists of an inner polyester fabric associated with a twisted tube around it, which is then filled with lighter-than-air gas. He suggested either He or NH3 as the filling gas to provide the role of the lifting force and proposed that such a floating solar chimney section could cope when combined to form super tall towers and be constructed for heights of up to 3000 meters. The folding lower part is also designed to bend freely against external winds and so can easily handle crosswind threats. It should also be noted that chimney height might be limited by annual average wind speeds and the potential deviation angle caused by prevailing crosswinds. FSC design has the following advantages [143]: a) Alleviating limitation of the chimney height based on materials, technology and cost; b) lower cost in comparison to conventional reinforced concretes; c) capacity of using smaller collectors due to unlimited chimney height as compensation and reducing collector construction and land costs and also limited areas in results; d) not affecting with seismic activities; e) improved overall performance even by lower apparent height in crosswind condition by reducing tip vortices and down-wash flows.

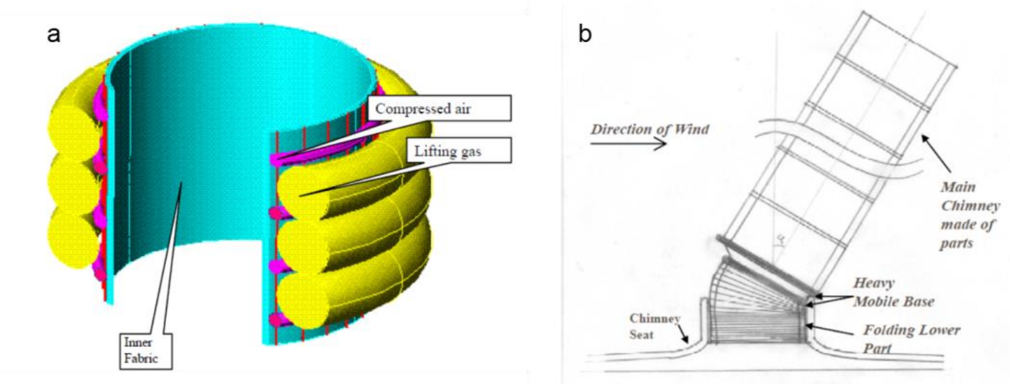


Fig. 18.(a) structure of FSC with over-pressed air tubes that retain its cylindrical shape and lifting gas tube to make a tall lighter than air cylinder [144]; and(b)configuration of FSC with folding lower part and floating chimney seat to deal with crosswind [138]

Zhou et al. [145] and Maghrebi et al. [146] also carried out an investigation into their economic aspects and estimated costs. Maghrebi showed that these floating power plants are able to be constructed at a large scale of up to 200 MW, with an annual capacity of 641 GW. In comparison, Putkaradze et al. [147] suggested an innovative self-supporting, free-standing and flexible solar tower constructed with air-filled stacks as a replacement for a vulnerable tall steel chimney, as illustrated in Fig. 19. In their model, the chimney no longer has a straight cylinder geometry but can deform, and such deformations are not concentrated just in the base of the chimney – unlike the former design.

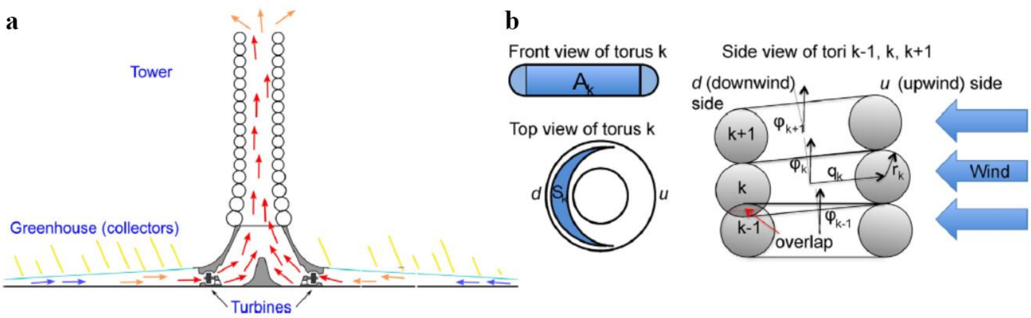


Fig. 19.Schematic of (a) solar chimney composed of toroidal bladders;(b) wind deformation mechanism shown [147]

Arefian and Hosseini Abardeh [143] proposed an experimental and numerical investigation to study integrated floating solar pilots for the first time (see Fig. 20a). They showed that floating solar chimney power plants (FSC) can operate more efficiently in windy conditions compared to conventional solid chimneys. This is explained by the eliminated tip vortices in the updraft tower and even overcame the lower apparent height in tilted conditions. Arefian and Hosseini Abardeh also declared that there is an optimum tilting angle for a specified design and also prevailing wind speed to minimize the adverse effect of the crosswind effect. They emphasized that finding this optimum tilting angle can enhance the operation of the floating solar chimneys significantly.

Chi et al. [148] developed a three-dimensional theory of motion for flexible solar towers and studied the stability and dynamics of the towers. The experiment prototype is illustrated in Fig. 20b.

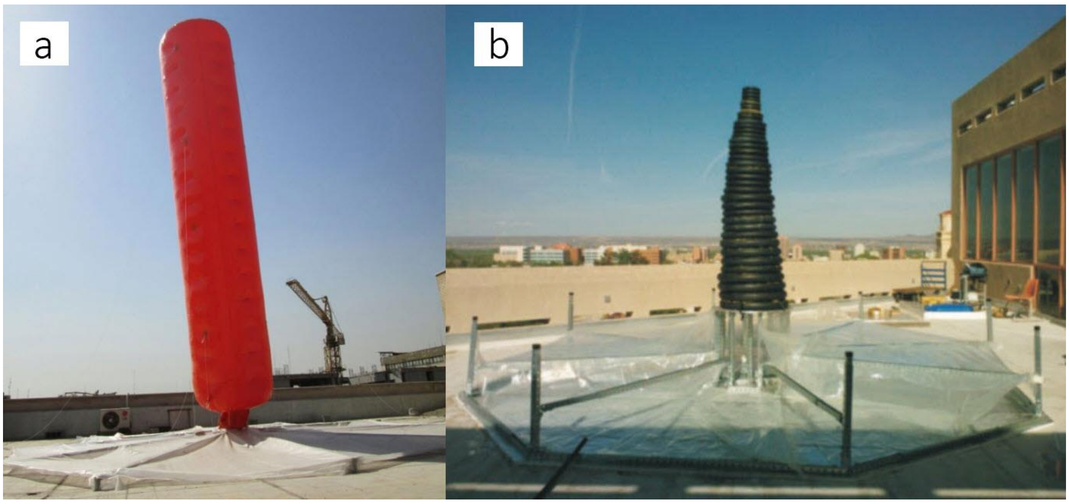


Fig. 20. Experimental setup of (a) floating solar chimney[143]; (b) flexible solar tower [148]

Another interesting and novel concept was proposed by Li et al. [149], in which they suggested a combination of tornado-type wind towers combined with a conventional SCPP. In this concept, the tornado-type wind tower is positioned at the top of the chimney to exploit deficits of pressure and thereby increase the updraft driving forces. Li et al. showed that the proposed prototype could decrease solar chimney power plant height by almost two times with a wind velocity of 15m/s. In conclusion, the hydrodynamic effect of wind speed enhances SCPP efficiency and could play a key role in solving one of the problems of tall chimney construction. The prototype is presented in Fig. 21a.

Another similar interesting novel concept to replace conventional chimneys is proposed by Louis Michaud [150, 151], called atmospheric vortex engine (AVE). Atmospheric vortex engines use the same working principle of solar updraft tower where the physical chimney is replaced by the centripetal force produced by swirly upward airflow. By taking advantage of the artificial convective vortex and producing natural updrafts in a vortex form, solar vortex engines are a potential choice to successfully replace the tall solar chimneys required in the SCPP [152, 153]. Fig. 21b shows an experimental setup of an atmospheric vortex engine proposed by Louis Michaud and Fig. 21c illustrates the mechanism of the atmospheric vortex engine.

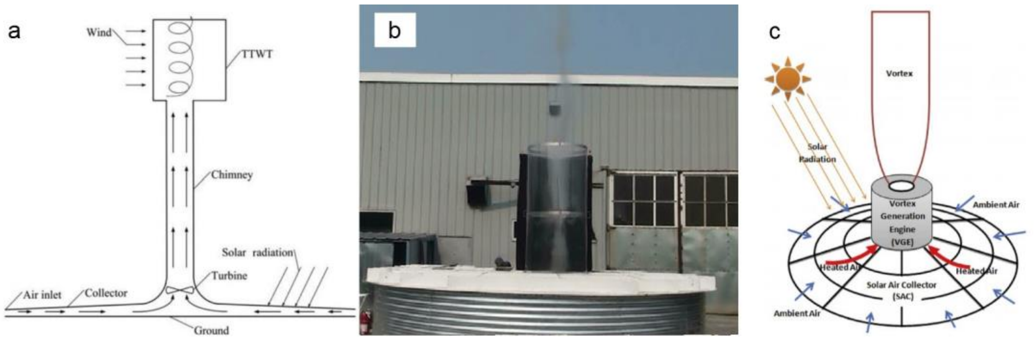


Fig. 21. (a) Combined tornado type wind tower and SCPP concept [149]; (b) experimental setup of atmospheric vortex engine proposed by Louis Michaud [150] ;(c) mechanism of atmospheric vortex engine [153]

Yet another suggested design to reduce chimney construction problems has been mentioned in Serag-Eldin (Fig. 22a [154]). The goal is to exploit the height of a mountain as a replacement for very tall, vertical chimneys, and all with no moving parts. With Serag-Eldin's proposal, the chimney utilizes the slope of the mountain and runs up a ground-laid duct whilst the collector spreads over valleys. In fact, with such a design, the collector is limited to semicircular geometry. The semicircular geometry design was also investigated experimentally by Khidhir and Atrooshi [155] with a modified collector model made up of one-third of the circular area.

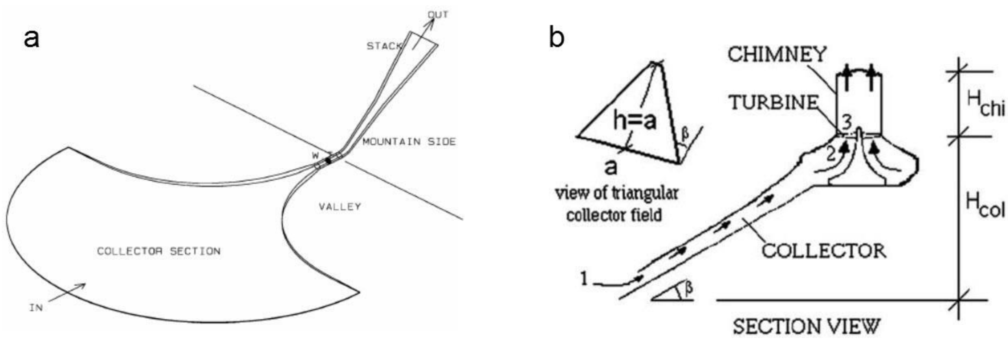


Fig. 22.Sketch of (a) proposed solar chimney design for mountainous regions[154]; and (b) solar chimney systems in a sloped surface at high latitudes[14].

Additionally, a sloped solar chimney has been produced by Bilgens (Fig. 22b [14]) for use in high latitudes. The main characteristic of this concept is a sloped triangular-section closed side collector which follows the line of the mountain or other natural slope. It was shown that this feature could then accept a solar chimney with a height up to half the height of the collector [156]. Jing et al. investigated the best slope gradient in this area [157]. Some researchers [45, 158-161] also carried out performance analysis of these systems, comparing sloped solar chimneys with conventional solar chimneys in China, Iran and other locations. Kalash et al.[162]

investigated the temperature field of a sloped solar updraft power plant experimentally. Xinping Zhou [163] studied the best curved profile fit for a mountain profile. He compared linear sloped collectors with a two-segment sloped collector and showed that the optimal sloping angle for reaching the maximum annual total solar radiation is lower than the local latitude.

A further novel concept in this area has been presented by Zhou et al. [164]. Zhou [165] suggested that a Solar Thermal Power Plant with a Floating Chimney rigidly mounted onto a mountainside alleviates some of the difficulties of floating SCPPs, and makes a smoother chimney line in mountain regions. The concept is shown in Fig. 23c.

Zhou et al.[166] proposed a novel concept of sloped solar collectors to improve the performance utilizing natural local upwind of warm air motion inside mountains. To profit natural valley-mountain wind in the sloped collector, SCPP should be located on the upper mountain slope (see Fig. 23a). In this concept, the solar chimney power plant can use the heat absorbed by the collector and the extra heat absorbed by the lower bare mountain slope. Findings revealed that by having a bare mountain slope of five times bigger, the collector area plant efficiency would increase by 183%. This method has shown a very interesting measure to enhance the efficiency and cost-effectiveness of sloped SCPP systems. The proposed novel concept is illustrated in Fig. 23b.

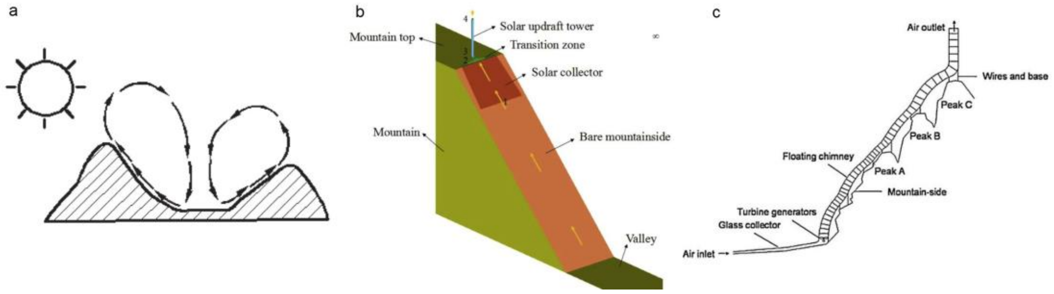


Fig. 23. (a) schematic of natural valley winds; (b) extraction of power from the natural valley–mountain wind by solar collector[166];(c) floating SCPP rigidly-mounted for a mountain region, schematic [165]

Papageorgiou (Fig. 24) [144, 167] proposed a modular Solar Collector for the solar chimney technology as a lower-cost alternative to the usual circular greenhouse pattern. The greenhouse will be made from a series of parallel reverse V or U-section glass panel tunnels leading to the entrance of the FSC. The modular solar collector diminishes on-site work and results in lower construction costs. It also could reduce dust problems and subsequent mud formation [168], which arise from a condensate film on the surface.

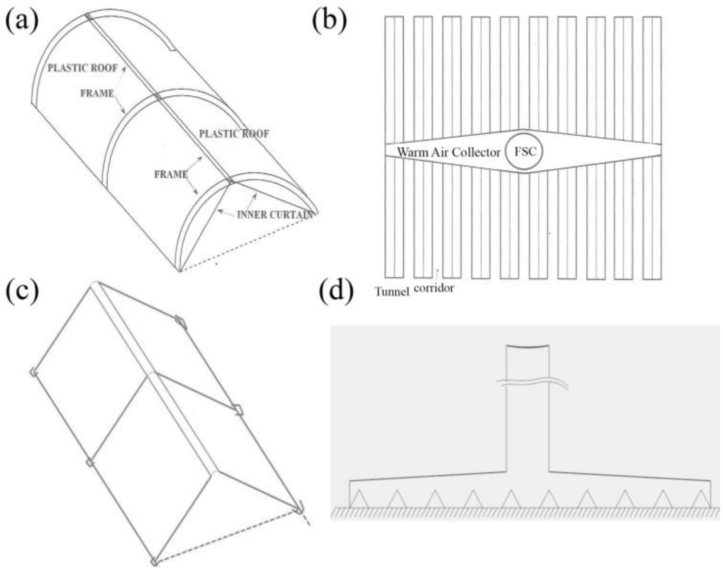


Fig. 24.Structural configurations of modular Solar Collector:(a)U type;(b)top view;(c)V type; and(d)front view[144]

Bonnelle [81] proposed a fresh concept to reduce turbulent friction inside the collector by utilizing a series of branching ribs, as shown in Fig. 25. Bonnelle's design for the collector entrance, possessing a larger area than a conventional collector, leads to lower velocities and hence helps reduce turbulent friction losses. At the same time, the collector roof can be installed at a lower height, offering the opportunity to reduce costs.

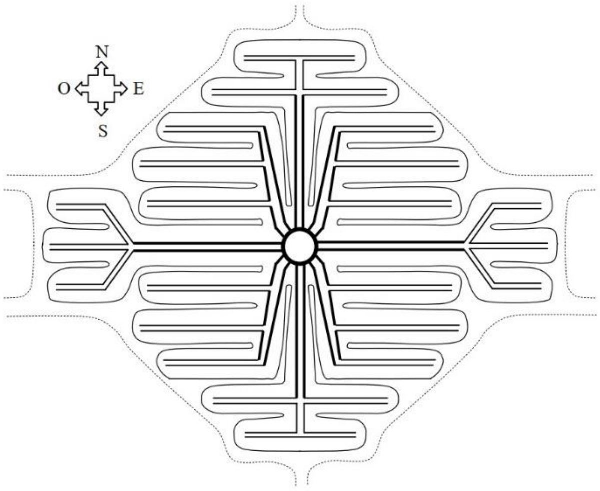


Fig. 25. Collector configuration with branching ribs [81]

Novel designs are introduced to alleviate the negative effects of the ambient wind on the flow characteristics of the air inside the collector and corresponding issues such as water and dust entry problems.

Singh et. al. proposed a novel design for collector inlets to enhance the performance and alleviate the mentioned problems of the ambient wind [110]. The so-called mouth-bell design as the fourth primary part of the SCPP systems along with the chimney, PCU and the collector refers to a bell-shaped configuration of the collector opening (see Fig. 26a), which is proposed in two types of horizontal and downward installation. Although horizontal configuration didn't show any significant improvements, downward configuration showed a surprising amount (33 percent) of velocity increase inside of Singh's proposed configuration, and by integrating with converging and diverging SCPPs, this amount had been raised to 270%. Singh also declared that the proposed integrating bell-mouth inlet in converging-diverging SCPPs could achieve the same order of velocity of the conventional SCPPs by 40 percent smaller chimney height and seven times smaller collector diameter of an upscale analysis of a 10MW SCPP. This novel design is backed up with financial incentives due to reduced size and land usage and material requirement, which is claimed to plunge the payback period to 41.5 percent lower than those of conventional designs. The reason behind the improvement of performance by Singh's bell-mouth design is considered to provide more uniform static pressure recovery along with the chimney height and improved capacity of handling more flow rates without recirculation zones formation.

Papageorgiou's patent [169] also take the best out of the new concept to replace the gigantic chimney cross-section turbine by a series of controlled air openings in the collector inlet.

Wherein the collector inlet is encircled by a peripheral enclosure, and a series of axial air fans, controlled by microprocessors, are installed to provide a controllable flow inlet (see Fig. 26b). Papageorgiou also suggested an electromechanical air stopping system in the opening to optimize power output by closing low-speed turbines so the residual air could be enhanced by the benefit of its now higher speed.

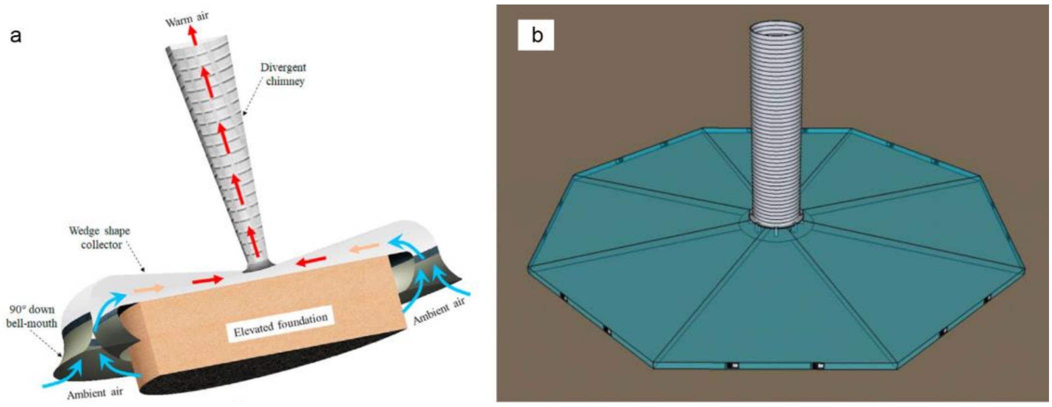


Fig. 26. (a) The novel bell-shaped configuration proposed by Singh et al.[110] ;(b) replaced gigantic turbine by a series of controlled air openings in the collector inlet proposed by Papageorgiou [169]

To investigate the effect of the crosswind on the performance of the solar chimney, many researchers have focused on flow patterns and thermophysical properties of the air both inside and outside of the chimney in the presence of the wind. Different studies have shown how crosswind can reduce the output power of SCPPs by plume deflection at the chimney exit and wind flow separation in downstream.

Arzpeyma et al. [170] investigated the effect of the chimney configuration on the performance of SCPP systems, particularly the effect of outlet bevel cutting angle. They studied the oblique angle of 27 to 45 degrees in wind velocity of 0-10 ms^{-1} to find the optimum design in which the throttling effect is suppressed the most. Their result illustrated how the optimum oblique angle is dependent on the wind velocity and increases with the increase of the wind velocity directly to obtain the best power output. They suggested an oblique angle of 27 for wind conditions of 10m/s and an oblique angle of 15 for 2m/s. Zhou et al. [171] investigated the effect of plume formation generated in solar chimney crosswind. They found that the relative humidity of the plume is increased due to entering into the colder surrounding. Thus, a condensation could occur, and precipitation would be formed. They also found that with the increase in chimney height or relative humidity of atmosphere or reduction of wind velocity, relative humidity increases and probability of the precipitation increases. After precipitation released latent heat from condensation can help the plume to rise. Illustrated streamlines and relative humidity field for chimneys with different heights of 1500 and 2500 m is showed in Fig. 27a.

RahimiLarki et al. [172] performed a performance analysis on a laboratory scale tilted solar chimney system exposed to crosswind. Even though the results showed that crosswinds generally have an adverse effect on the performance of the conventional solar chimneys, titled solar chimneys performed a better flow performance at the tilting angle of 10°-20°. The findings also revealed that at 15° tilt angle, power output increased from 5 to 20 percent compared to conventional straight towers at the exact same crosswind velocities. The study cleared that the relatively weak crosswinds have a negative effect on the performance by the formation of tip vortices at the chimney outlet and thermal energy loss from the collector. Furthermore, at the higher velocities, ambient crosswind causes suction at the chimney outlet and enhances updraft airflow. Thus, the performance deteriorates less dramatically in higher ambient crosswinds. This trend continues to the point (30° in the mentioned study) that apparent chimney height is considerably affected and the performance suffers from low efficiency of shorter chimney rather than improved suction from the crosswind.

Arzpeyma et al. [173] reported that there is a maximum amount for the velocity in the turbine for different crosswind velocities. This maximum amount for velocity in the turbine is reported to be highly dependent on the chimney oblique angle and occurs in higher crosswinds by increasing the oblique angle. Clearly, higher oblique angles also show higher velocity in the turbine.

Investigation of the crosswind effect on the performance of the atmospheric air purification tower is done by Zhu et al. [174]. Atmospheric air purification tower is an inspired concept of SCPP. Zhu et al. investigated three wind-breaking designs and showed that union-jack-shaped windbreak wall is the optimal design (see Fig. 27b). Zou et al. [175] also suggested that a circular blockage a few meters in front of the collector entrance can slightly boost power generating capacity in strong crosswinds.

Zhou et al. [176] also studied the effect of the baffle near the collector entrance and discussed flow patterns and vortexes. They showed that the baffles could reduce the amount of heat loss due to ambient wind blowing through the collector and heat loss is much less than the case without baffle.

Arefian et al. [143] investigated the crosswind effect on the floating solar chimney and determined optimal tilting angle at specified crosswind speed to maximize velocity enhancement. Contours of velocity magnitude and streamlines for the conventional and floating solar chimneys are illustrated in Fig. 27c.

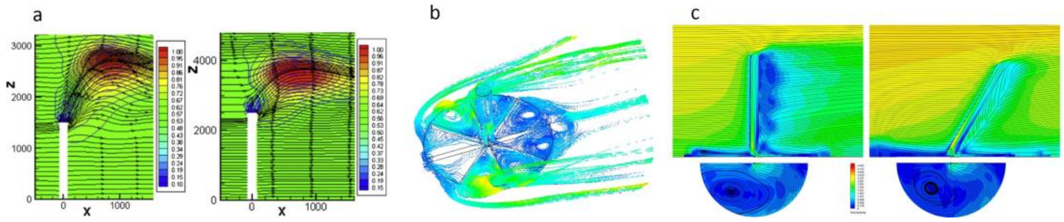
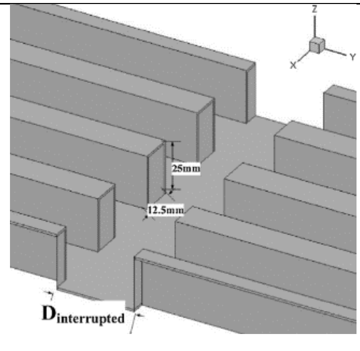
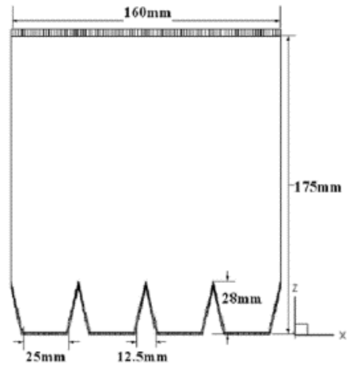
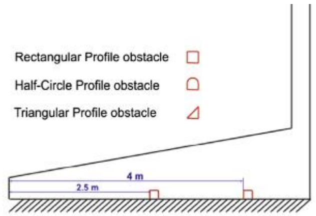


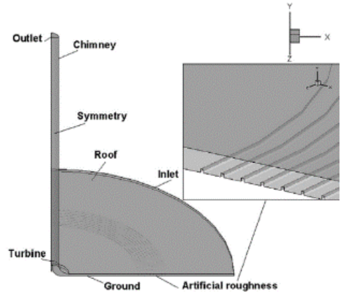
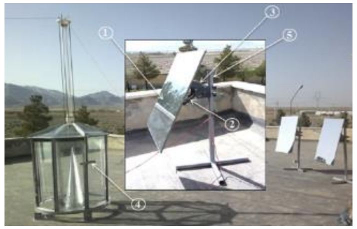
Fig. 27. (a) Illustrated streamlines and relative humidity field for chimneys with different heights ;(b) investigation of the crosswind effect on the performance of the atmospheric air purification tower [174];(c) Contours of velocity magnitude and streamlines for the conventional and floating solar chimneys [143]

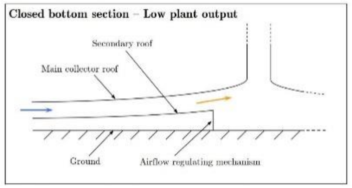
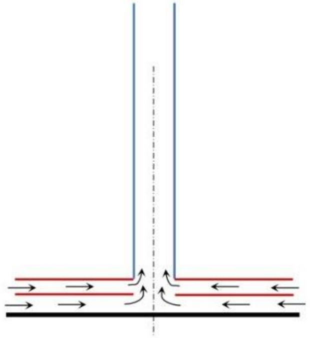
Aja et al. [177] investigated the effect of wind speed on an inclined south-faced solar chimney, experimentally. Considering the wind direction, the study findings showed a performance degradation for winds prevailing from east or west and a more severe performance reduction for the north to south winds. However, the study revealed the south to north winds favored the performance due to more wind air entering the collector. They also suggested using guide vanes to prevent wind from sweeping off the hot air inside the collector in adverse wind directions as a solution.

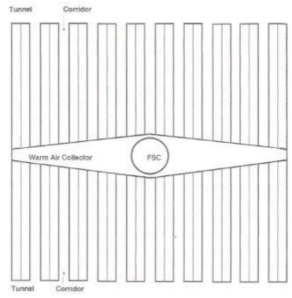
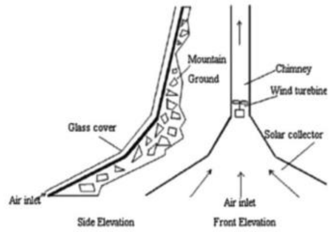
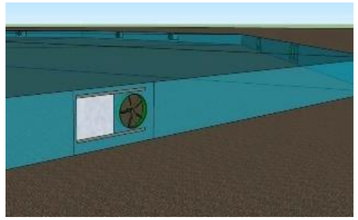
Table 2 shows the advantages, disadvantages and prominent features of suggested auxiliary techniques.

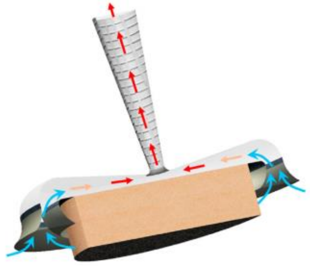
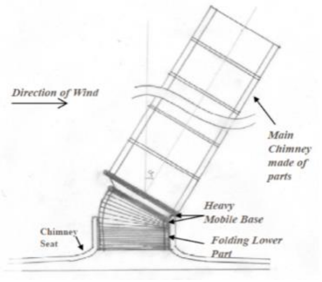
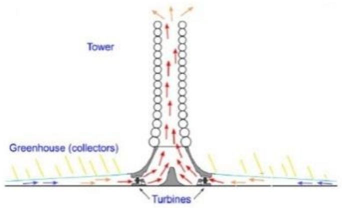
Table 2. Advantages, disadvantages and prominent features of suggested auxiliary techniques

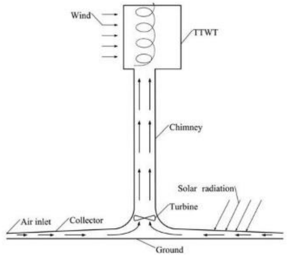
	design	Description	advantages	disadvantages	improvement	Schema	ref
Flow mixing enhancement	rectangular fin	Effect of longitudinal Continuous and discontinuous type of rectangular fin installation in absorber have been studied	-efficiency improvement by increasing the depth ratio of field (heat transfer area) -heat transfer coefficient improvement due to disturbance and reformation of boundary layer	-maintenance difficulties due to hard access inside the site -excess material usage in fins -higher pressure drop	- thermal performance improvement by the increasing number of fins - efficiency improvement by increasing the depth ratio of fins -performance enhancement in discontinuous type by appropriate interruption gaps		[122]
	Different fin shape	triangular, elliptical and rectangular fins effect in natural convection solar air heaters	-increasing thermal efficiency by redirecting the flow	-manufacturing difficulties in unconventional fin shape -maintenance difficulties due to hard access inside the site -excess material usage in fins -increasing in pressure drop	-The thermal efficiency of the solar air heater with rectangular fins is 5.5% higher than elliptical and triangular fins		[123]
	Passive flow control implementati on	different shape obstacle implementation such as half-circle, rectangular and triangular	-altering the flow field and improving mixing inflow by secondary flows and vorticities.	-flow blockage in obstacles	- increasing velocity rate and consequently energy output improvement up to 41.2% - An obstacle with a triangular profile supplies more thermal performance enhancement since the flow		[124]

					pattern was guided toward the chimney.		
	artificial roughness	Considering the optimal location for artificial roughness due to velocity reduction despite heat transfer improvement	-either with natural roughness like ground surface or by artificial roughness such as energy storage system roughness has an inevitable impact - it can take advantage of existing components like water pipes - the existence of roughness has a positive impact on the performance of the power plant When the wind is blowing	-reduction in velocity	-installation artificial roughness near the collector entrance has a better influence on efficiency		[125]
Incoming radiation increase	Intensifier's utilization	utilizing intensifiers to intensify heat flux and air tank to increase absorption of reflected solar radiation	- higher heat flux entered the solar chimney by utilizing an intensifier	-utilization in small SCPPs due to collector shape and intensifier height limitation -ray tracing reflectors apparatus difficulties	-two times increment in maximum velocity compared with a without-intensifier prototype		[130]

	Reflector's utilization	A SCPP with enhanced incident solar radiation aided with reflectors	-higher input flux temperature and mass flow rate	-limitation in reflectors high in large scale SCPPs	- the gain in efficiency was increased up to 22 percent compared to conventional solar chimney power, ten percent floor temperature increment and 134 percent increment in mass flow rate -133%power output increment		[132]
Secondary roof supplement	Transformative closure	Transformative end closure in underneath roof	-warm trapped air acting as an energy storage medium	-controllable mechanism difficulty for transformative end closure end			[72]
	Double roof	Parallel and counter flow mechanism	-more heating due to the longer path in counter flow type and exposure to warm air instead of ambient	-more pressure loss due to longer path			[127]

Novel collector design	Modular U type collector	Utilizing a series of long U or V type glasses	-prevent dust layer formation and consequent problems -low cost and with lesser working in site difficulties	-higher pressure loss			[178]
	sloped SCPP	Sloped SCPP along with mountain profile	-better companionship with mountain ups and downs -chimney behavior of collector due to rising				[158]
	Enclosed SCPPs	A closed collector entering containing a number of the axial fan instead of large-scale turbines	-lower cost due to complex turbine section deletion such as gearbox -external wind altering - optimized power output by a controlled electro-mechanical air stopping system - convenient repair and maintenance	-low-efficiency fans and a higher number of components	- crosswind secured thermal storage layer		[169]

	Bell-mouth design collector inlet	A novel design of inlet provides the potential of uniform static pressure along with the chimney and cease recirculation formation in the outlet	-33 percent overall performance improvement -preventing crosswind and associated dust and water entrance and other repercussions	-Elevated foundation costs	-novel Bell-mouth inlet converging and diverging integrated solar chimney		[110]
Novel chimney designs	Floating SCPP	Chimney filled with lighter than air gas makes the possibility to lift off and tilting in crosswind	-relative negative pressure in outlet due to crosswind and providing a good driving force -alleviating heavy solid problems -alleviating crosswind concerns	-lowering SCPP height in tilting operation mode			[138]
	toroidal bladders chimney	tubes with sliding possibility in crosswind interaction	-relative negative pressure in outlet due to crosswind and providing a good driving force -alleviating crosswind concerns	-lowering SCPP height in tilting operation mode			[147]

Tornado wind tower combined	Tornado wind tower installed at the outlet to make a favorable driving force	-relative negative pressure in the outlet and providing a good driving force -ability of utilizing smaller SCPPs	-low improvement in low wind speed region	-providing power output up to a twice height size		[149]

Regarding the vast potential of the solar chimney systems in meeting different industrial needs, solar chimneys can overcome air pollution problems in megacities as well. Even though the final solution to the particulate matter problem is to replace fossil fuels with sustainable and renewable energy resources, many techniques are currently under study to enhance the efficiency of the combustion systems such as HCCI, RCCI, hydrogen addition and etc. to mitigate air pollution in cities [179-182]. Nevertheless, developing societies and public health issues cannot wait until the time that fossil fuels are completely phased out and replaced or NOx and PM particles in combustion systems reach their minimum. Solar chimneys can relieve the heavy burden of haze and pollutions in megacities and alleviate public health risks along with corresponding constraints in developments in economic and industrial developments.

Preliminary estimates revealed that just nine solar chimneys would be enough for transferring atmospheric air below 1 km over Beijing to a higher altitude in three months [183]. Liu et al. [184] reviewed geoengineering measures in mitigating air pollution strategies based on the solar chimneys, which are considered to have large-scale pollutant elimination ability. Some geoengineering measures include driving polluted air into the troposphere by penetrating the planetary boundary layer [183], water spraying on the top of the solar chimney to scavenge pollution [185], Solar chimney with condensed water from vapor in the air [74, 186] and large filter usage in air driven by solar chimney [187, 188]. Liu et al. [184] considered these four measures as some practical methods to handle air pollutant issues at low cost, without any negative trace in the environment and without requiring special weather conditions.

Compared with traditional methods, mitigating air pollution strategies based on solar chimneys enjoy some big advantages such as continuous operation during the day and night without intermittency, clean and environmentally friendly, producing electricity as a byproduct and very low maintenance for long periods.

It is revealed that high solar chimneys can avoid the growth of fine particulate matter (PM2.5) and haze formation by opening meteorological channels for pollution dissipation to a long distance [189, 190]. In this case, the chimney must be tall enough to penetrate the planetary boundary layer (~1000m), which can be handled by floating chimneys.

Solar chimneys with water spraying can remove particles in the air at relatively low water loss because collected water can be used as rainwater. Sufficient water resources and spraying systems are required[191]. Solar chimneys with air filter are another practical method to eliminate acid gases pollutants as well as aerosols. In this method, air filters for specific pollutants should be designed and replaced regularly[192, 193].

In addition to solar chimney pollutant mitigating methods, the atmospheric vortex engine proposed by Louis Michaud [150, 195]–which has the same working principle as a solar chimney–can generate a cyclone column to replace high chimneys and avoid responsible high construction costs and failure concerns.

In Fig. 28a, a picture of a solar-assisted large-scale cleaning prototype in Xi'an, China, with a filtering efficiency of 73.5%, is presented [187]. Airflow containing haze in the presence of urban heat and updraft tower is shown in Fig. 28b [183]. Furthermore, Gong et al. proposed a 200m solar updraft (see Fig. 28c) with the spraying section at the end of the ordinary solar updraft towers to bring the clean air back to the level where human activity takes place and not to the upper level of the atmosphere [195]. This concept is called an inverted U-type cooling tower.

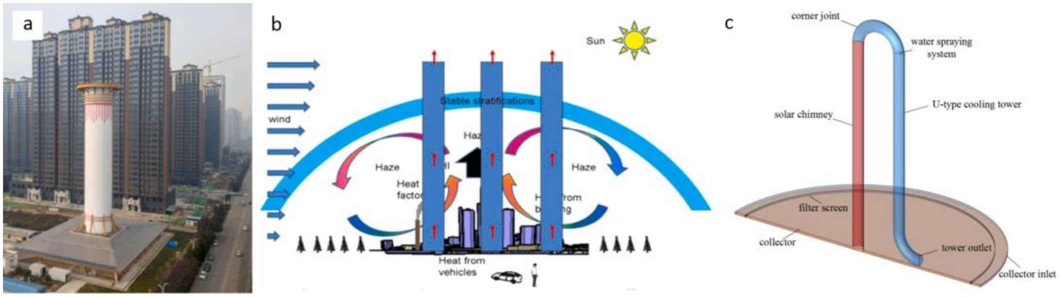


Fig. 28. (a) solar-assisted large-scale cleaning prototype in Xi'an[185] ;(b) Airflow containing haze in the presence of urban heat and updraft tower [181];(c) inverted U-type cooling tower [193]

3.3 Hybrid SCPPs

Because sunlight is not available for all hours of the day and is also reduced on cloudy days, researchers have considered how to reduce these effects and allow some form of 24-hour operation without intermittency. There are reports on combining technologies, for example, using fuel cells, thermal energy storage, geothermal effects, photovoltaic cells, wind power technologies etc., with solar, thus creating multi-objective systems such as water desalination and solar drying procedures etc.

3.3.1. Desalination

Desalination of impure water is one simple, cheap and useful way of using brackish water. However, water desalination is limited by factors such as the need for large-area solar distillation plants, low water production rates per unit area and the natural restriction of limited solar radiation in some regions [196]. According to the report from International Water Association (IWA) published in 2016, water desalination can cut costs (as shown in Fig. 29) since it is becoming an effective way of solving water demand problems in areas with high water salinity levels [197-199]. However, at this time, integrated SCs with water desalination is not yet practical, and this promising hybrid needs further studies. That being said, cost forecasts over the next 15 years show a considerable reduction in construction costs, electrical energy usage, etc., as shown in table 3.

Table 3.Costs of desalination for medium and large projects[199].

Parameter for Best-in Class Desalination Plants	Year 2016	Within 5 Years	Within 20 Years
Cost of Water (US$/m^3)	0.8 – 1.2	0.6 – 1.0	0.3 – 0.5
Construction Cost (US$/MLD)	1.2 – 2.2	1.0 – 1.8	0.5 – 0.9
Electrical Energy Use (kWh/m^3)	3.5 – 4.0	2.8 – 3.2	2.1 – 2.4

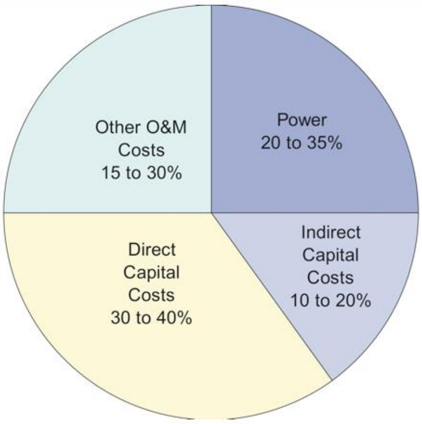


Fig. 29.Desalination cost breakdown[199].

Despite the limited studies in the solar chimney for desalination, the early results are promising. The practice of water desalination is at the center of attention in the contemporary agricultural industry and domestic sector and attracted much attention regarding extensive usage of solar desalination units already in use (18,500 plants in 2018) and declining prices due to systematic R&D researches [200]. Furthermore, solar chimney power plant desalination systems enjoy the construction of simple and accessible materials, which are of high interest in less developed countries, where the building of sophisticated systems needs a higher technological base level. These systems also take advantage of high solar resources in a relatively less developed country, which cannot employ other more sophisticated desalination technology and are even more exposed to environmental factors such as dust, contrary to other systems with mirrors and lenses involvement. In spite of the great work in solar chimney systems, these systems still suffer from low energy conversion (0.5%-10%), as do many other solar energy systems. Hybrid solar chimney desalination plants can derive needed water in site at the expense of lowering the power output due to a reduction in airflow temperature. Nevertheless, solar chimney desalination systems can incorporate into seawater systems. In this case, the system is not much different from conventional solar chimneys, where a rock layer works as an energy absorber at the bed and the energy is substantially transmitted into the water pond below the collector to warm up and evaporate the water. This vaporized water is handled to condense on the inner surface of the cover to obtain usable water. Zuo et al. [201] estimated annual power output of 2.83×105 and the annual freshwater of 69,500 tons for a system of 200m height chimney and 250m diameter collector.

Zuo et al. evaluated two types of hybrid systems, 1) a wind supercharging SCPP with seawater desalination and waste heat, 2) SCPP integrated with seawater desalination and waste heat [202]. They investigated the proposed models both experimentally and mathematically to estimate the efficiency of hybrid systems. The results in the research of Zuo et al. are as shown in table 4.

Table 4. Comparing results and the evaluated parameters by Zuo et al. [202]

Investigated parameter	**Results**	**Comparison**
Increase in chimney’s height	Water desalination improved Power generation improved	---
Increase in solar irradiance	Water production decreased Generated power improved;	---
Decline in seawater depth while enough solar irradiance exists	Water desalination improved Power generation improved	---
Increase in the temperature of the exhaust gas	Water desalination improved Power generation improved	---
Performance	---	WSCPPDW was better than SCPPDW about 15%

Ming et al. [203] proposed a solar chimney power plant that replaces the greenhouse canopy with black tubes filled with water. The system’s principal works like the mechanism of formation of clouds. When air rises, the temperature drops and, accordingly, the relative humidity. When the chimney is built high enough, the air reaches the dew point and condensed water is formed in a solid surface to be collected. In this proposal, the black tubes can act as a thermal storage platform like the soil in conventional solar chimneys. Ming et al. [186] modified the previous prototype later on and suggested using two kinds of turbine; one wind turbine to generate power, and one hydraulic turbine to extract power from freshwater in downstream. The consideration between power and water production is an intricate matter in solar chimney desalination systems. It is proved that although the heating in airflow increases temperature and airflow in favor of improving power output, but the relative humidity decreases with increase in temperature and a higher chimney is needed to allow the airflow reach its dew point for water production. To alleviate this problem, in another study, Ming et al. [204] suggested spraying of heated water under the canopy to produce a warmer air condition at the entrance. Both works of Ming is illustrated in Fig. 30.

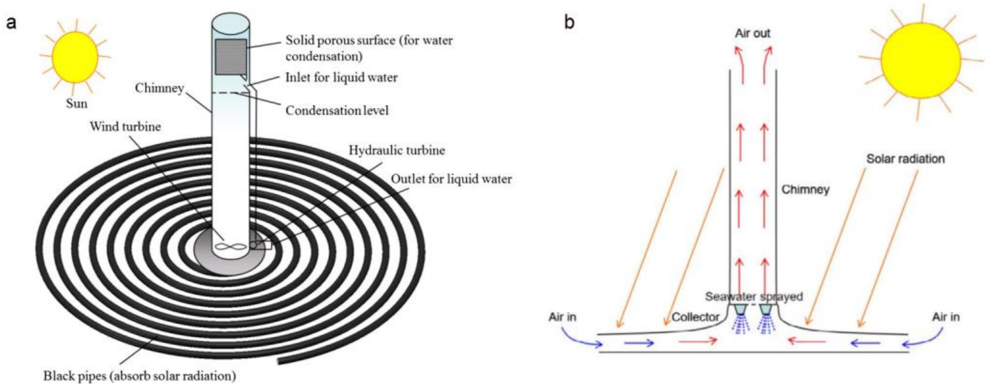


Fig. 30. (a) SCPP proposed system with a coil of black tube working as the solar collector; [186] (b) Sketch of the Seawater Desalination Mechanism of the Solar Chimney System with seawater spraying [204]

3D studies are also attempting to reflect the impact of structural parameters better than previous mathematical models. In a parametric study, Zuo et al. [205] investigated the impact of turbine rotational speed, the nozzle length, the chimney outlet radius and the chimney mixing section length, and reported 377.9 kW power output with 20.3ton/h freshwater for a 194.6 chimney height and 122m collector radius solar chimney desalination system. In other studies, the influence of guide vanes also revealed that these design parameters could enhance the productivity of the system [206]. It was found that the guide vanes can significantly increase the freshwater productivity and power output by mitigating airflow rotation after the turbine. Research progress on integrated solar chimney systems for freshwater production is still in its infancy. However, there is a growing interest among scholars to develop this promising technology in different types of solar chimney freshwater production such as Open-type solar still, Closed-type solar still and freshwater harvest from the atmosphere, to name a few [207]. Many studies attempt to study the economic parameters and installation site's actual condition to find the optimum design of solar chimney desalination plants as well [208].

3.3.2. Drying Technology

Solar drying dates back to 8000 BCE when the first solar dryer was installed in France. In an energy-conscious world, solar drying is becoming a necessity because of its major merits, such as no requirement for fuel or electric power. Drying is an activity that consumes lots of energy in its broader production applications, for example, textile manufacture [209], brick production [210], cement production [211], and wood and timber treatment [212] etc. Solar drying therefore offers yet another option for switching to a more eco-friendly method rather than using fossil fuels. Sandali et al. reviewed the enhancement of solar drying systems by various techniques and factors in multiple solar dryers, such as direct, indirect, mixed-mode and hybrid dryers [213]. At the same time, the effect of different climate conditions, geometry, heat exchanger and heat pumps, reflector addition, phase change material

(PCM) and etc., were also evaluated. The results of which, showed that climate conditions and solar radiation had the greatest impact.

Afriyie et al. investigated the performance of a solar dryer experimentally [214]. In their research, they performed their tests firstly in a cabinet dryer, followed by tests with a chimney. Eventually, the trials were conducted with a tent dryer in which the roof of the drying chamber was inclined. Afriyie et al. also monitored effective factors such as air velocity, temperature, relative humidity, and the moisture content in a crop.

Afriyie et al. divided their experimental tests into two different categories, namely no-load and under-load tests. In the under-load category, there were four different subcategories as follows:

- Test-set 1: tests on the dryer with roof angle 81°, using the normal chimney.
- Test-set 2: a repeat of Test-set 1, but with the solar chimney.
- Test-set 3: using the roof angle of 64°, still with the solar chimney.
- Test-set 4: using the roof angle 51°, still with the solar chimney.

Under-load tests were conducted in the presence of the root crop cassava.

In table 5 shows the dryer in no-load conditions.

Table 5. Conditions of the dryer in no-load tests [214].

	No absorber	**With chimney absorber**		
	`Test-set 1	Test-set 2	Test-set 3	Test-set 4
Roof angle (°)	81	81	64	51
Ambient air temperature (℃)	21.83	23	22.17	23.5
Dryer exit air temperature (℃)	26.83	31.33	29.5	30.83
Inlet air relative humidity (%)	57.17	42.17	51.67	42.33
Dryer exit air relative humidity (%)	38.17	26	34.17	24.83
Ambient air velocity ($\boldsymbol{m/s}$)	0.02	0.01	0.02	0.01
Dryer inlet air velocity ($\boldsymbol{m/s}$)	0.14	0.18	0.19	0.2
Dryer exit air velocity ($\boldsymbol{m/s}$)	0.39	0.45	0.49	0.52

Afriyie et al. concluded that a solar chimney crop dryer is advantageous because it is cheap to construct and that its performance is enhanced when the relative humidity of the ambient air falls. However, conversely, performance is reduced when relative humidity is high [214].

3.3.3. Photovoltaic Cells and SCPPs

Rahbar and Riasi proposed novel configurations of conventional solar chimney power plants (CSCP) coupled to a photovoltaic cell (PVSCP) and brackish water desalination (PVDSCP) in order to utilize solar energy more effectively [215]. In their study, Rahbar and Riasi developed a 1-D mathematical model for each configuration and then validated their mathematical results by experimental results. The studied geometry is shown in Fig. 31.

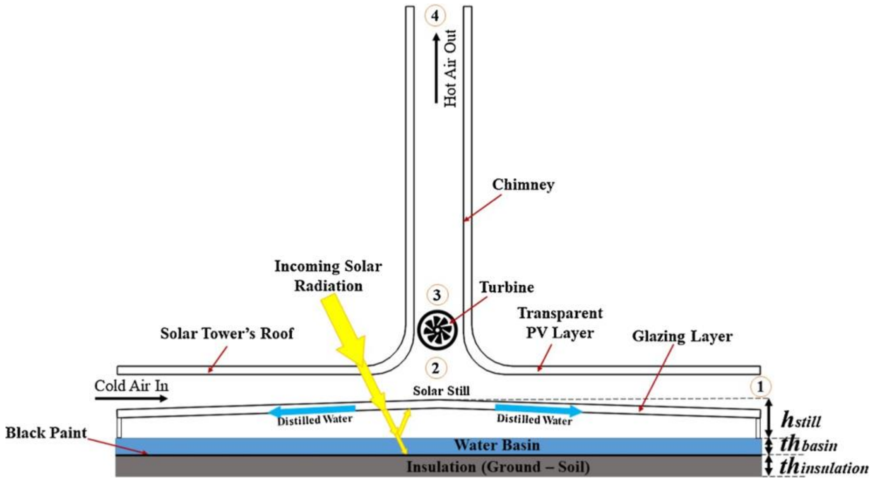


Fig. 31. Schematic detailed geometry of the PVSCP and the PVDSCP [215].

From their results, it is revealed that a PVDSCP is more efficient than a CSCP and a PVSCP by 26.13% and 21.92%, respectively. In contrast, the efficiency of the turbine is higher than the CSCP and PVDSCP by about 17.9% and 31.3%, respectively. Key parameters in their optimization were the roof radiation, roof height, tower radiation, tower height, and mass flow rate. After comparing the optimization with the Manzanares solar chimney power plant [43], their results showed that utilizing a PVSCP and PVDSCP in Manzanares could improve the efficiency of the power plant 55.97% and 71.8%, respectively.

Using fluid dynamic analysis, Haghighat et al. evaluated different PV panels in four different locations in a SC [214], and their investigated parameters (as shown in Fig. 32), included the location and the widths of the PV panels within the SC. Three different PV widths of 70, 50, and 30 cm were tested, and the 50 cm cell proved to offer the best results, in that when the transparent collector was replaced with the 50cm width PV cell, the efficiency is increased by 1%.

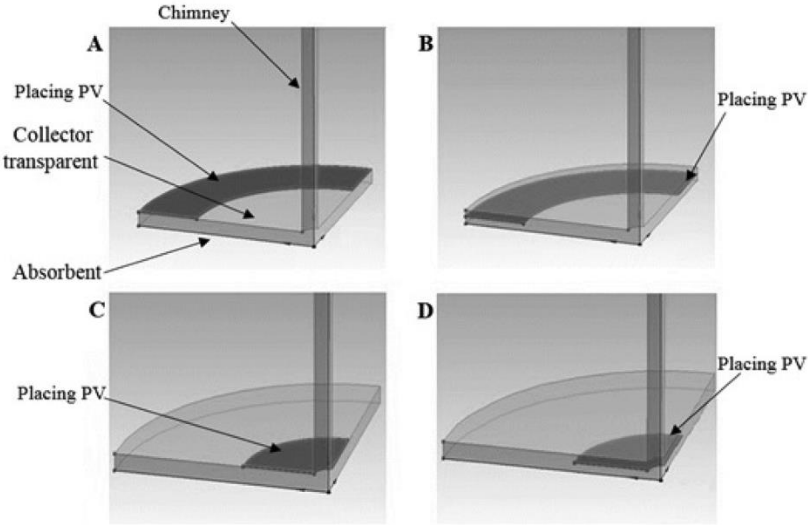


Fig. 32.Investigated parameters by Haghighat et al.[214].

Ahmed et al. proposed a new design for a chimney in Kirkuk, Iraq [217] by constructing two types of experimental models. In the first model, the collector roof is made of glass, and a PV panel was installed as an absorber, whilst in the second model, the collector roof was made of PV panels and used plywood as the absorber. They observed that the useful power from the second model was greater. The use of photovoltaic panels in the solar chimney also takes advantage of the better cooling effect in optimized configuration shapes of the solar chimney. Optimum solar chimney shape showed an effective impact on the cooling of these panels besides its hydrodynamic merits as Singh et al. [218] suggested a hybrid solar chimney with converging collector and diverging chimney with bell-mouth collector inlet design and showed PV panels enjoyed 8 to 12 °C decrease in temperature.

3.3.4. Ventilation

In applications related to ventilation, the most examined parameter is the airflow rate. Nguyen and Wells analyzed the flow rate and thermal efficiency of using hybrid SCs to ventilate buildings through CFD simulation [219], their evaluation dimensions being chimney length, air channel gap, inlet height, outlet height, inlet width, and outlet width. Results showed an increase in flow rate is possible with increased absorber surface length, air channel gap, and heat flux, but a drop in thermal efficiency for the outlet width – due to flow reversal at the outlet.

Serageldin et al. performed a parametric study, which included optimization methods for heating and ventilation systems through CFD, as shown in Fig. 33 [220]. In this research, they validated their results against an experimental result in the cold season on March 14-22, 2016, in Egypt.

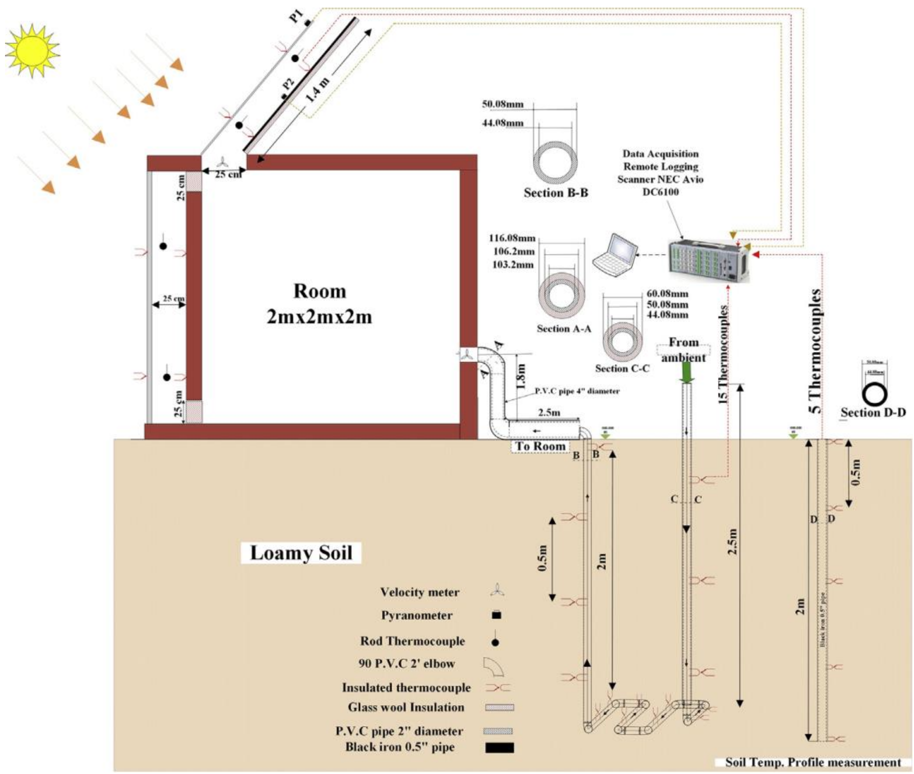


Fig. 33. Schematic of the studied geometry by Serageldin et al. [220].

In their investigation, they optimized the system through the central composite design of the experiment algorithm (CCD) and found eight parameters with which to maximize the ventilation rate for the solar chimney configuration and earth-to-air heat exchanger design, these being: width, length, air gap, inclination angle, position and pipe diameter, inlet position, and inlet height. The most sensitive parameters are (in order) EAHE pipe diameter, chimney height, EAHE height and position, solar inclination angle, width, and gap. They also concluded that the optimum chimney inclination angle, length, width, and gap, lie within ranges of 30–35°, 1.94–1.97 m, 0.92–0.97 m, and 0.19–0.23 m, respectively.

Kong et al. examined the variation of the inclination angle of a SC installed on a roof, looking to enhance its performance for ventilation purposes using CFD-based methods. The work considered two cities in Australia – Adelaide airport, Darwin, and Townsville Aero [221], and Kong et al. performed their simulations under four different heat fluxes, 200, 400, 600 and 800 W/m^2, together with the impact of various inclination angles, $30°, 45°, 60°, 75°$ and $90°$, respectively. They reported two main conclusions as follows: 1) In real-life related applications, the inclination angle exerts a profound influence on the received solar irradiance and the ventilation efficiency. 2) In their numerical evaluation, the greater the inclination angle, the greater the space ventilation as a result.

Wang et al. described a hybrid SC for ventilation [222]. They examined four main parameters through a CFD approach, namely the thickness of the glass panel, the width of the air gap, the thickness of the water columns and surface tinting. Their results showed that by cutting the thickness of the glass panel in half, the ventilation was enhanced by 7.3%. In addition, that up to 0.2 m increase, either in the width of the air gap or the thickness of the water column, boosted the ventilation rate by 21%. Proper ventilation also is crucial to public health issues, particularly in unforeseen pandemics such as coronavirus. Lipinski et al.[223] reviewed ventilation strategies to reduce the risk of disease transition. Passive stacks and solar chimneys are classified in natural ventilation measures, which can displace air and supply fresh air practically.

3.3.5. Power Generation and wind turbine

Electrical power is generated through a complex heat transfer process where solar energy is converted to electrical power. Coupling turbine blades with a SC can generate power which is a free and durable source for power generation and Tingzhen et al. numerically analyzed a SC coupled with a turbine [224]. In their study, they investigated the effect of turbine rotational speed on the outlet of the chimney. They also considered, by simulation, the design and performance of a MW-graded SCPP with a 5-bladed turbine. The results showed an efficiency of 50% at a power output of 10 MW. Xu and Zhou developed a mathematical model for their performance investigation into a modified solar chimney power plant (MSCPP) used for power generation and vegetation growth purposes, the schematic for which is shown in Fig. 34 [18]. The evaluated parameters were solar radiation, ambient temperature, relative humidity, and chimney height.

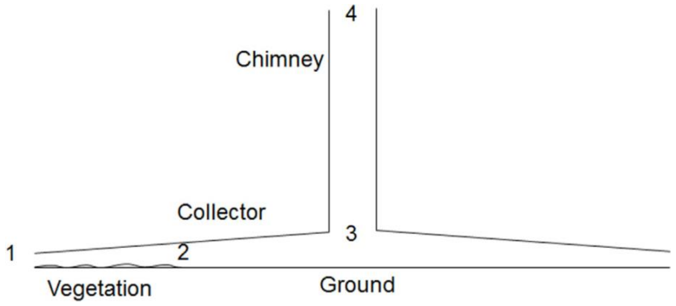


Fig. 34. Schematic of the modified solar chimney power plant, vegetation is grown in some parts of the collector [18].

They validated their simulation results via the experimental results of Haaf [43]. Results show that an increase in vegetation area results in an increase in the mass flow rate of the vapor and leads to a considerable reduction of power. Furthermore, when the weather is cooler, the production of power also falls. Further, when the relative humidity is higher, the mass flow rate of the evaporated vapor from the vegetation area decreases, but power generation increases. Finally, they concluded that a modified solar chimney power plant is more advantageous than a conventional SCPP.

Wahab and Al-Maliki studied the capability of utilizing a SCPP in a farm to produce electrical power for agricultural demands, such as pumping systems, irrigation, and lighting, etc. The study was performed using Ansys software and was compared with the results obtained from an experimental farm condition [225]. Wahab and Al-Maliki concluded that the experimental farm SCPP, with collector dimensions of 70 m × 50 m and the chimney height of 20 m, had produced electrical power at its highest level in a year, at about 29 kW [225].

Tian et al. analyzed a hybrid SC in a desert city, Yazd, located in Iran [226]. In this research, they optimized the SC economically using a deer hunting optimization algorithm whilst comparing these optimization results with the genetic algorithm and particle swarm algorithm of MATLAB software. Tian et al. proposed two days, in July and in February, in order to analyze the hottest and the coldest days in the desert region of Yazd. From the results, they concluded that on the hottest day in July, owing to the high intensity of the sunlight, the produced energy is comparable with the coldest day in February.

Negrou et al. investigated the thickness distribution of blades and the desired swirl distribution [227] which was proposed by Wu [228]. The goal of their research was to design the turbine blades based on the dimensions of the existing prototype suggested by Manzanares [5], which then speeds up the optimization design for a SC. Also, the incompressible non-viscous flow was studied as part of their research. Fig. 35 shows the studied geometry and the generated mesh in their model.

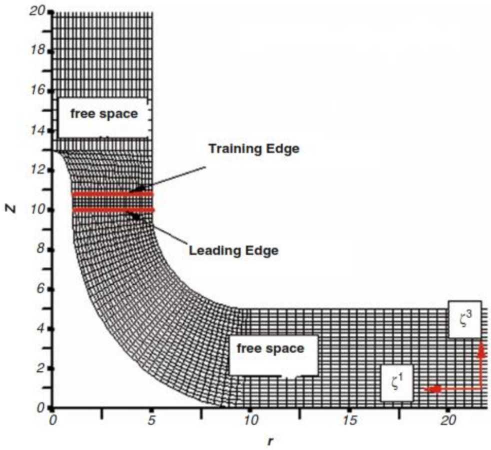


Fig. 35. Studied geometry by Negrou et al. [225].

3.3.6. Cooling Systems

Nasri et al. designed a new system based on the integration of a SC and a solar-air conditioning system [229]. The system works upon the principles of adsorption chilling and desiccant dehumidification, and as part of the investigation, the authors theoretically considered the proposed system under real conditions related to Tunisia. The test was performed on four different days, and on each occasion, the air temperature decreased, and the relative humidity increased during the pre-cooling and cooling processes, respectively.

Hweij et al. studied the efficiency enhancement of cooling a window using a solar chimney, analyzing and predicting the window temperature and its impact on comfort under the conditions in an office space located in Riyadh, Saudi Arabia [230]. There were two representative hours, 14 h and 17 h, for this hot, dry climate. The results showed that thermal comfort was improved by the provided system. When the system was present at 14 h, the thermal comfort reached 1.42. However, and for comparison when the proposed system was absent, in order to reach the same level of thermal comfort (1.42), a similar space was considered where all the conditions were constant, but the supply temperature was kept variable. Likewise, when the system was present at 17 h, the comfort level was 1.96. The work showed that the proposed system saves energy by approximately 10% (see Table 6).

Table 6. Saved energy at 14 h and 17 h [230].

Cases	**Overall thermal comfort**	**Energy-saving (%)**
14 h	1.42	9.64
17 h	1.96	9.8

3.3.7. Water Harvesting

Ming et al. suggested a modified solar chimney that can generate freshwater in addition to generating power [203], and the proposed chimney design has undergone experimental tests within nine different cities in China. The work looked at the moist air, which condenses above the lifting condensation level, and of a one-dimensional compressible flow and the heat transfer mathematical model developed. The work showed a direct correlation between the precipitation of the environment and the water produced by this system – in general, the modified system increasing water production by a coefficient of 0.875. Furthermore, they observed that the system is also effective in arid regions, and Table 7 indicates a convincing increase in the ratio of water production to natural precipitation across all nine cities.

Table 7. Natural precipitation (NP), water production (WP), and the ratio of WP/NP at nine stations in 2013 [203].

	NP (mm)	**WP (10^0t)**	**WP (mm)**	**Ratio (WP/NP)**	**Sunshine duration (h)**
Chengdu	1343.3	29.71	5942	4.42	1128.8
Shanghai	1173.4	23.62	4724	4.03	1864.7
Shijiazhuang	508.3	17.08	3416	6.72	1716.8
Zhengzhou	353.2	12.87	2574	7.29	1925.6
Wuhan	1434.2	29.37	5874	4.10	2092.5
Chongqing	1026.9	27.40	5480	5.34	1213.7
Beijing	579.1	14.59	2918	5.04	2371.1
Urumqi	300.9	8.18	1636	5.44	3068.6
Guangzhou	2095.4	37.92	7584	3.62	1582.9

Wu et al. proposed a modified solar chimney power plant, called a "Aero logical Accelerator" (AeAc), which utilizes the latent heat of a condensation process [231]. Using a mathematical model, the potential energy and generated water at different ambient temperatures were conducted, and their results (Fig. 36), show that the system can generate both water and electrical energy for domestic usage if the right method is used for collecting the water. As such, electrical energy generation depends on the temperature of the entering heated air and the system size. Furthermore, water generation is determined by the relative humidity at the entrance of the chimney in addition to the aforementioned factors.

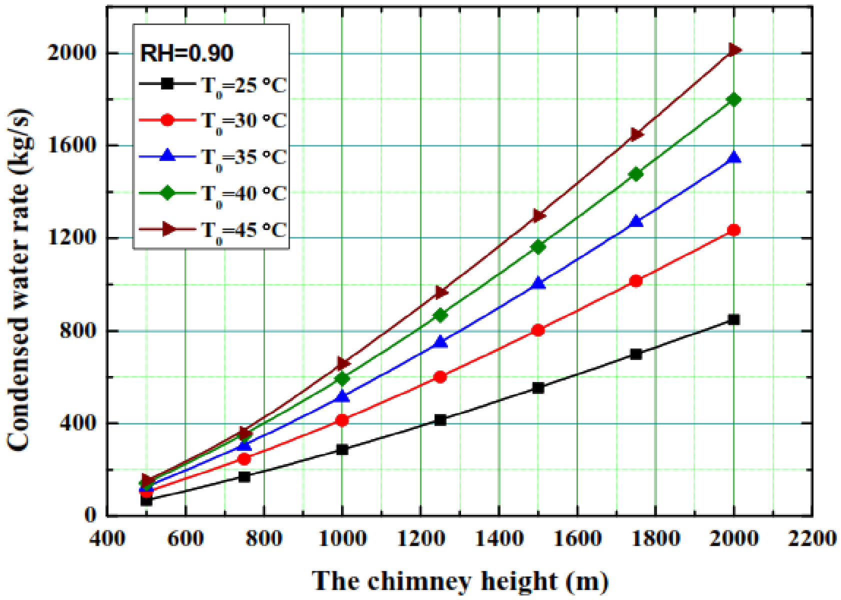


Fig. 36. Rate of condensed water vs. chimney height at RH= 0.90 [231].

Hoseini and Mehdipour numerically analyzed the effect of solar radiation and water temperature on power generation and water harvesting for two different cases, namely (1) integrating a SC with a humidifier and (2) coupling a chimney with a humidifier and a condenser [232]. In the conducted research, they concluded that, in the first case, by utilizing a hybrid SC, the generated power rises with increasing solar radiation and that it increases at least 1.3 times higher than with a typical SC when the water temperature is at a minimum of 10 °C. In the second case, they found that as solar radiation grows, the amount of harvested water declines.

4. **Conclusion**

Solar chimney power technology is a simple thermal technology involving three main components: the solar chimney, the solar collector and a power conversion unit. However, despite being a straightforward and eco-friendly technology, its low efficiency remains an important practical drawback. Accordingly, solutions to this problem have drawn much attention in order to harvest greater power output and lower spending costs. This work aims to present a comprehensive and the most recent, detailed and applicable studies, including experimental, theoretical, simulation and reviews, which cover new design concepts along with configuration suggestions for efficiency increments.

The crucial point that emerged from the experimental studies, is that most of the constructed SCPPs are built at a small scale and are not capable of utilizing potential improvements that are inherent with larger systems via economies of scale because most of the system parameters are strongly dependent on the construction problems that would occur with larger scale plant, such as the chimney divergence angle.

However, despite their low efficiency (for SCPPs, less than 2%), some researchers have focused on improving the overall efficiency through the enhancement of individual parts of the system. Hence with such an aim in mind, many design parameters have been considered within each section, including changes to profile for both chimney and collector segments. Novel ideas such as utilizing fins, obstacles, reflectors and secondary roofs for the collector, in addition to the floating chimney, different profile shapes and new configurations for chimney have been reviewed as well.

Therefore, as a part of developing a guideline for future researches and closing the gap in SCPPs technology studies, it is suggested to study different ideas combined together, particularly with ideas that don't interfere, such as the effect of fin and Bell-mouth inlet collector, influence of floating chimney and converging angle of chimney and impact of mountainside collectors and intensifiers. The parametric studies are mainly focused on the primary factors and basic configuration of SCPP subsystems or aim to investigate one auxiliary technique solely, and studies suffer from combination of novel ideas and basic components' alteration deeply. The process of reviewing classified novel ideas and component basic alteration for individual components of solar chimney power plant systems can help researchers to develop new designs based on the different combinations. This can help the SCPP designers to optimize the overall performance of the system by improving each component's corresponding efficiency. Furthermore, increasing the efficiency of one component to the maximum level can overcome the other one's efficiency depletion due to construction limits. The implication of this work can also help to build future prototypes and optimization of each component based on the overall performance, construction limits and locations to guide the building of the next industrial SCPP system.

In some studies, the low-efficiency imperfections have been reduced by integrating a SCPP with other systems, and these are categorized into eight main groups, namely: 1) Water Desalination Systems, 2) Drying Products, 3) PV Collectors, 4) Ventilation Systems, 5) Power Generation Systems, 6) Geothermal SC, 7) Cooling Systems, and 8) Water Harvesting. Water desalination can reduce the costs of providing water in some arid regions. The integration of SCPPs and dryers is also an option since solar energy is an eco-friendly, durable and free source. The other types of hybrids SCPPs are power generating SCPPs which can generate electricity from the sun by a simple replacement in the collector, e.g., installing turbine blades in the SC. Ventilation in buildings and chilling systems is another usage of hybrid SCs that can enhance the efficiency of the ventilation and the cooling system in addition to generating free power. The other important function of hybrid SCs is water harvesting that is one possible solution to the ever-increasing problem of the water crisis which is spreading across the world. In Fig. 37, a summary of the conclusion on discussed solar chimney systems is gathered in a wider view.

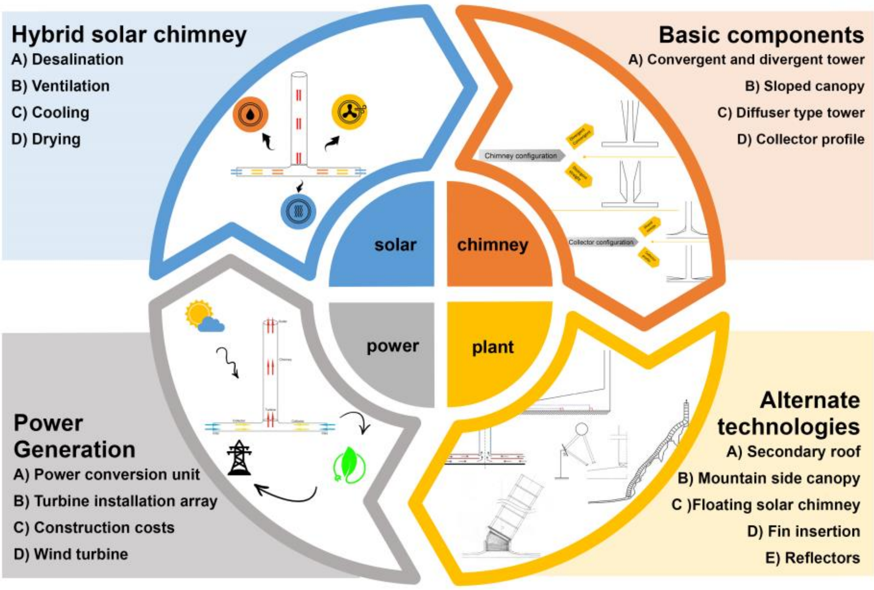


Fig. 37 Different major categories in solar chimney systems, component optimization, alternate technologies and hybrid solar chimneys.

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