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New Approaches in Solar Chimney Power Plants: Recent Applications of Hybrid Power Production

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ABSTRACT

The importance of solar energy is increasing day by day for humanity, considering the increasing environmental pollution with the intensive use of fossil fuels in recent years. While the importance of solar energy is increasing, the development and effective use of existing solar energy systems are also important. There are many systems in which solar energy is used directly or indirectly. Solar chimney power plants (SCPP) are systems that indirectly generate electricity from the sun by transferring solar energy to the air in its structure. It is promising with its low maintenance costs and environmentally friendly working principles after its installation. This study firstly explains the working principle of the system to the readers and then evaluates the parameters that affect the performance of the system. The effect of the collector and chimney, which are the main elements of the system, on the performance of the system in different geometries and designs is interpreted based on the literature. Then, it refers to the innovative studies carried out in recent years regarding the system. As a hybrid system, studies such as adding PV modules to SCPP systems, adding geothermal and external heat sources, desalination of seawater, and obtaining clean water are included. The effect of hybrid systems on performance is evaluated. It is seen that the power output of the system reaches satisfactory levels with PV, geothermal, and external energy source reinforcement. In addition, its use for different purposes such as obtaining clean water is promising.

Keywords: Solar chimney power plants, Hybrid SCPP systems, Solar hybrid systems, Solar Chimneys, Solar chimney performance

Güneş Bacalı Santrallerde Yeni Yaklaşımlar: Hibrit Enerji Üretiminde Son Uygulamalar

ÖZ

Güneş enerjisinin önemi fosil yakıtların son yıllarda yoğun kullanımı ile artan çevre kirliliği göz önüne alındığında insanlık için her geçen gün artmaktadır. Güneş enerjisinin önemi artarken mevcut güneş enerji sistemlerinin geliştirilmesi ve etkin kullanımı da önemlidir. Güneş enerjisini doğrudan ve dolaylı olarak kullanıldığı birçok sistem mevcuttur. Güneş bacası güç santralleri (SCPP) güneş enerjisini yapısındaki havaya aktararak dolaylı olarak güneşten elektrik üreten sistemlerdir. Kurulumundan sonra düşük bakım maliyetlerinin olması ve çevre dostu çalışma prensipleri ile gelecek vadetmektedir. Bu çalışma ilk olarak sistemin çalışma prensibini okuyuculara açıkladıktan sonra sistemin performansını etkileyen parametreleri değerlendirir. Sistemin ana elemanları olan toplayıcı ve bacanın farklı geometri ve tasarımlarda sistemin performansa olan etkisi literatürden hareketle verilerek yorumlanır. Daha sonra sistem ile ilgili son yıllarda yapılan yenilikçi çalışmalara değinir. Hibrit sistem olarak SCPP sistemlerine PV modül ilavesi, jeotermal ve dış ısı kaynağı ilavesi, deniz suyu tuzdan arındırma ve temiz su eldesi gibi çalışmalara yer verilir. Hibrit sistemlerin performansa etkisi değerlendirilir. PV, jeotermal ve harici enerji kaynağı takviyesi ile sistemin güç çıkışının tatmin edici seviyelere ulaştığı görülür. Ayrıca temiz su eldesi gibi farklı amaçlar ile kullanımı gelecek vadetmektedir.

Anahtar Kelimeler: Güneş bacası güç santralleri, Hibrit SCPP sistemler, Hibrit güneş sistemleri, Güneş bacaları, Güneş bacası performansı maddesi

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1. Introduction

The increasing human population in the last century has led to the rapid consumption of energy resources. This situation will cause CO_2 emission and environmental pollution to reach a level that will negatively affect human health in the future, due to the fact that energy sources are predominantly fossil fuels. In recent years, researchers have searched for energy that can be an alternative to fossil fuels. The first of these alternatives is undoubtedly the endless source of energy, the sun. The sun is a favourite of researchers both because of its high potential and because it is the easiest source of energy to reach in the world. Numerous studies have been conducted on the possibility of benefiting from solar energy in many different ways. Solar energy can be used in two different ways, directly and indirectly. It can be used directly for space and hot water heating, as well as generating electricity through PV systems. There are also solar energy systems that can indirectly generate electricity through some systems. PV systems convert solar radiation and photon energy into electrical energy through semiconductors (Sheik et al., 2022). Systems that directly benefit from solar energy are solar cookers, solar dryers, solar pools, solar stills, water purification and distillation, solar air conditioning, etc. (Cuce et al., 2022a). In systems where electricity is produced indirectly from solar energy, solar energy is transferred to a fluid in the system. Then electricity is produced from the kinetic energy of the fluid through the turbine. In solar towers, the sun's rays are concentrated to a point using heliostats, and the condensed heat is stored and transferred into a cycle (Alexopoulos and Hoffschmidt, 2017). Another system that can indirectly generate electricity from solar energy is solar chimney power plants (SCPP). These systems, which transfer solar radiation on it through a transparent collector to the air inside, work by rising the heated air and leaving the system through the chimney (Cuce et al., 2020a; Cuce et al., 2022b). Meanwhile, the kinetic energy of the accelerating system air is converted into electricity through the turbine. Although its theoretical background is very old, the first example of SCPP, which has been put into practice recently, is found in Manzanares, Spain (Haaf et al., 1983). It has been shown by experimental measurements that the system with a collector diameter of 244 m and a chimney height of 194.6 m gave a power output of 50 kW in September (Haaf, 1984). After the Manzanares prototype, many studies on the system were made by researchers. These systems are not very common compared to other solar energy systems. This is because their yield is relatively low. The efficiency of these systems, which have a large collector area, exceeds the level of 1% with the height of the chimney reaching 1000 m (Mullet, 1987). Despite being criticized for its low efficiency, there are numerous studies on the system. When the studies are evaluated, the effects of the changes in climatic and geometric parameters on the system are examined by the researchers. While climatic parameters include ambient temperature and solar radiation intensity, geometric parameters are related to the dimensions and design of the system. In previous studies, the authors evaluated the performance parameters of SCPP systems from past to present (Cuce and Sen, 2020). They make some recommendations for performance improvement by integrating domestic products into the system (Cuce et al., 2020c). Although some parameters improve the performance of the system, new developments make the use of hybrid systems inevitable.

When the studies on SCPP systems are examined, it is seen that there are new approaches recently. It is seen that hybrid systems are created by adding different systems to the SCPP content, especially in order to increase the low efficiency of the system. This study aims to present a review to the readers by combining traditional methods and new approaches to improve the performance of the system. In this way, while the changes in the performance of the system are interpreted with traditional methods, it is aimed to inform the readers about the hybrid use of clean energy sources with new approaches.

2. Studies on SCPP Systems

2.1 Traditional Studies

SCPP systems work by increasing the temperature of the system air under the transparent collector using solar radiation. The temperature increase of the system air has a direct performance-enhancing effect. Therefore, an increase in solar radiation intensity is expected to lead to an increase in performance. Similarly, it is an application that can be done to increase the collector size in order to get more energy into the system. In Table 1, the researchers' studies on the geometric parameters affecting the performance of the system and the findings they obtained are given.

Table 1. Working examples for traditional SCPP systems.

References	Worked parameters	Results
Belkhode et al. (2020) Cuce et al. (2020b) Ahirwar and Sharma (2019)	Chimney height	Increase in chimney height improves systems performance
Torabi et. al. (2021) Sen et al. (2021)	Collector size	Increasing collector size improves SCP's performance
Cuce et al. (2021a) Toghraie et al. (2018)	Chimney radius	An increase in chimney diameter rises power output. Increasing the chimney diameter after a point decreases the performance of the system. The chimney diameter value has an optimum range
Semai et al. (2017) Hassan et al. (2018) Semai et al. (2017)	Collector slope	The inclination of the collector improves the performance of the system compared to the horizontal situation. However, if the collector slope is more than a certain stream, it has a negative effect.
Cuce et al. (2021b) Hassan et al. (2018) Torabi et al. (2021)	Divergent and convergent chimney shape	Divergent chimney design increases the performance of the system, while convergent chimney design decreases the performance. The chimney divergence angle adversely affects the system after a certain level.
Cuce et al. (2020c) Cuce et al. (2021c)	Ground slope	The sloped design of the floor of the system has a positive effect on the performance. The rise of the floor towards the chimney inlet increases the power output as it supports upward air movement. However, there is a maximum value for it.
Cuce et al. (2022c)	Energy storage on the ground	Natural ground materials such as basalt and Bayburt stone have a positive impact on the thermal effects beneath the collector area, which yields better performance characteristics with cost reduction.

However, when studies are detailed, some effects become limited. The chimney is the driving force of the system (Sen and Cuce, 2020). It is expected that the increase in the chimney height will increase the performance continuously, but contrary to the expectations, the increase in the chimney height does not increase the performance of the system after a point (Al Alawin et al., 2012; Yapıcı et al., 2020). Similarly, although the increase in the collector area increases the energy entering the system, the increase in the collector size after a certain point has a negative effect on the performance of the system (Cottam et al., 2019; Najm and Shaaban, 2018). Researchers have done performance improvement studies with different designs on the system. It is claimed that the SCPP system to be installed on a sloping ground will perform better than the systems installed on a horizontal ground (Guzel et al., 2021). Researchers have also done many studies on climatic parameters. Changing the climatic parameters only by location cannot be used to improve the performance of the system. It is predicted that only SCPP systems installed in regions with locally high solar radiation and low ambient temperature will give more power output (Cuce et al., 2020a). Numerous studies of researchers show that system performance increases significantly with design parameters. Despite this, new approaches offered by rapid developments in renewable energy allow the establishment of much more efficient systems with systems integrated into SCPP systems. In the next section, hybrid systems are mentioned in this direction.

2.2 Recent Studies on SCPP Systems and Its Applications

There are numerous applications related to solar energy. The most important factors in the use of applications are economy and efficiency. SCPP systems are systems with low efficiency due to their structure. For this reason, with the integration of some systems, researchers both try to increase efficiency and create new designs using SCPP in order to obtain additional energy. These systems, which are called hybrid systems, can generally be given with the following titles; integrated PV systems, seawater desalination, hot gas injection, integrated heat exchanger, integrated geothermal systems, gas turbine add-on systems, and integrated flue-gas.

2.2.1. Integrated PV Systems

Researchers create hybrid systems with PV modules added to the floor of the SCPP or on the collector. Haghighat et al. (2019) integrate PV modules into a small-scale SCPP system with a CFD study. They claim that there is an increase in the performance of the PV system, which is due to the air movement in the SCPP. Jamali et al. (2018) evaluate the performance of the system by making the collector of the SCPP system from transparent PV. The view of the system is given in Figure 1.

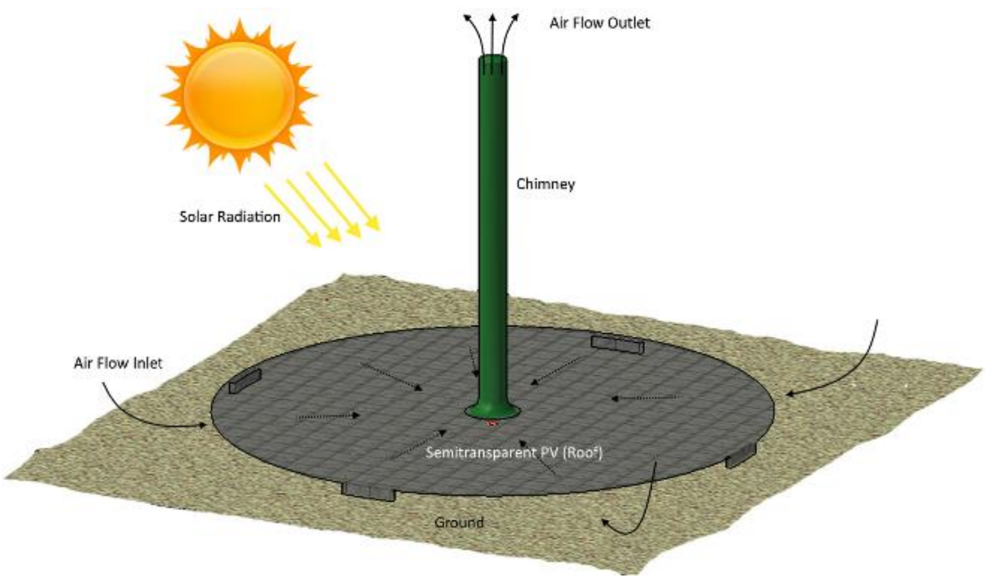

Figure 1. SCPP system view using PV panels as collectors (Jamali et al., 2018).

They emphasize that there will be a 29% improvement in the electricity production of the PV system with the design. Liu et al. (2018) use the solar chimney for cooling PV modules. They state that the PV power coefficient increased by 4.47% with the installed system. It is seen that the power output changes when the ground is covered with PV at different rates, and sizing is required for the ideal situation. Eryener and Kuscu (2018) evaluate the performance of the system by placing PV modules on the collector of the SCPP system with an experimental study. The top view of the system is given in Figure 2. They compare the performance of independent PV systems based on the data they have obtained from the hybrid system for 18 months. They emphasize that the efficiency range of the system is 16-18% and it is much more efficient than traditional SCPP systems. Some researchers use their small-scale SCPP systems to cool PV modules (Boutina et al., 2018; Hussam et al., 2022).

Figure 2. Top view of PV integrated SCPP system (Eryener and Kuscu, 2018).

2.2.2. SCPP Systems with Geothermal and Waste Heat Reinforcement

SCPP systems are systems that convert solar energy into heat energy. One of the applications that can be done to increase the performance of the system is to increase the temperature of the system air under the collector by using an additional heat source. For this purpose, geothermal energy or waste heat can be used. Since geothermal energy can be used 24 hours a day, it can also be useful when there is no sun, as it will provide energy to SCPP systems. Cao et al. (2014) evaluate the effect of geothermal resource addition to the Manzanares pilot plant on the performance of the system. Details of the system are given in Figure 3. They claim that the geothermal-added SCPP can provide 24-hour power output in all seasons and double the power output of the system with a source at high temperature and flow. According to Habibollahzade et al. (2021) evaluate the improvement in the performance of the system when a geothermal heat source is integrated into the Manzanares pilot plant by conducting a CFD and mathematical study. They show that the power output of the pilot plant will be between 3-7 kW at night, and with the addition of a geothermal source, the power output will be 82.6 kW at night and 192.1 kW during the day.

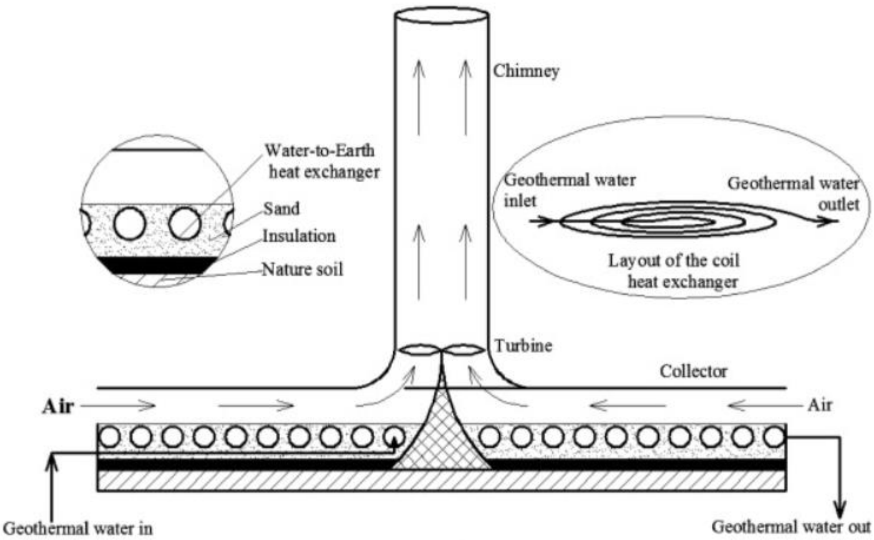

Figure 3. Hybrid SCPP system with geothermal energy addition (Cao et al., 2014).

Fatih et al. (2018) claim that by using the waste heat of a nuclear power plant in the SCPP system, power output can be obtained for 24 hours. They emphasize that in the CFD study based on the Manzanares pilot plant, the power output of the system will increase by 150% annually compared to the reference situation. According to Habibollahzade et al. (2018) designed a hybrid system that can be powered at night by integrating the waste heat from the condenser into the SCPP system. The addition of the system to SCPP with single, double, and triple pipes is given in Figure 4. In their study, in which they refer to the Manzanares pilot plant, they claim that the double pipe reinforced system gives maximum performance. They show that during the day the power output will increase by 20% compared to the reference SCPP system, and in the evening, it will increase by 120%. They state that the system will output a minimum of 20 kW at night.

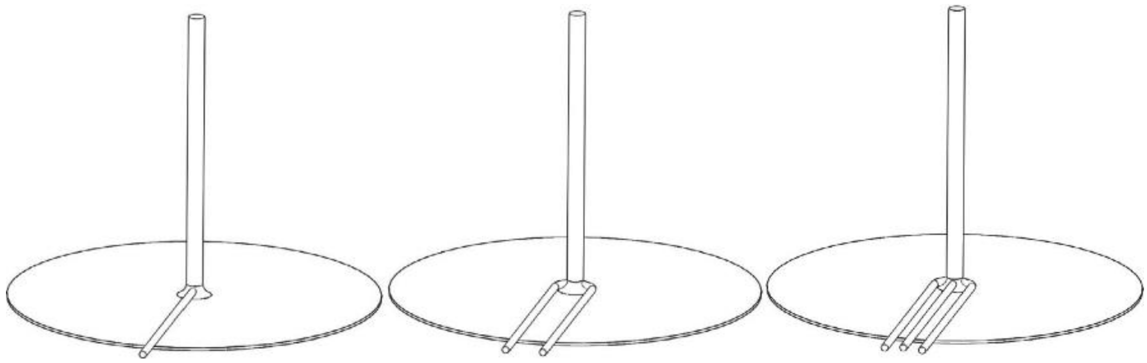

Figure 4. Waste heat loadings, and air injection under the turbine with different pipe quantities (Habibollahzade et al., 2018)

Yazdi et al. (2021) make a small-scale SCPP study with flue gas addition with a 3D CFD study. Dimensioning and visual details of the system are given in Figure 5. They claim that with the addition of flue gas to the system, the mass flow rate will increase by 7.63% and the power output by 11.48%. Aliaga et al. (2021) evaluate the performance of the SCPP system modified with the heat exchanger by CFD study. They show that there will be a significant improvement in the performance of the system with the heat exchanger they place in the chimney. They place a 2000 W electric heater inside the 2 m high chimney. This value is obtained from sun mirrors with an area of 2 m2 at a radiation intensity of 1000 W/m^2. They claim that with the hybrid system, 59% more power output will be obtained from the Manzanares pilot plant.

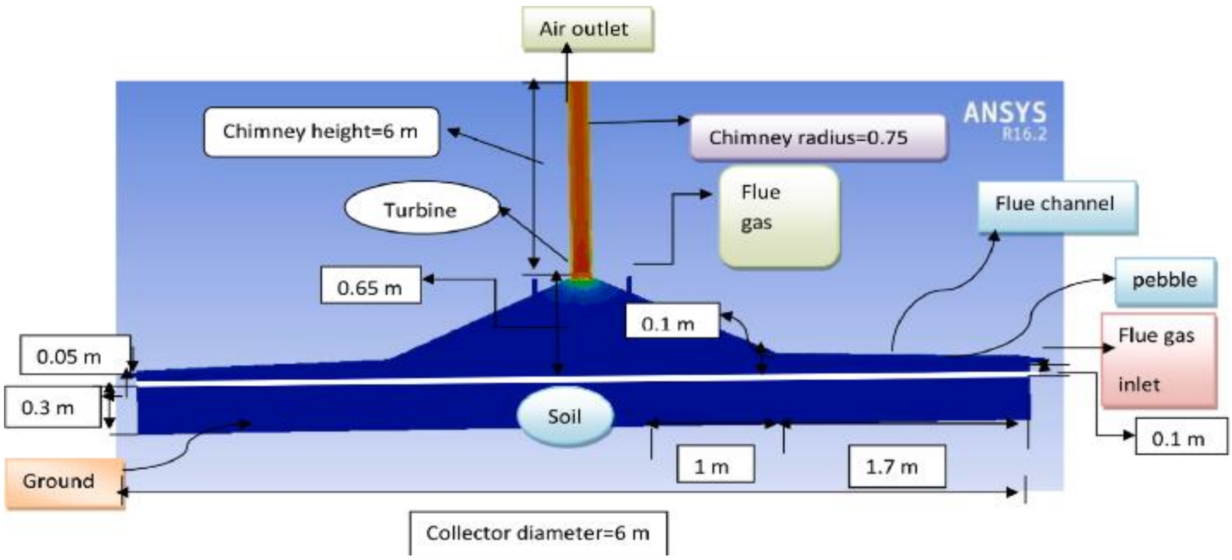

Figure 5. Flue gas integrated SCPP and system details (Yazdi et al., 2021).

2.2.3 SCPP Systems Installed for Desalination of Seawater and Obtaining Clean Water

Solar energy can be used not only for energy but also for different purposes. Obtaining water is an important problem, especially in arid regions where solar energy potential is high. Researchers use the SCPP system to desalinate seawater and obtain drinking water. Zuo et al. (2011) combine the SCPP system with desalination to generate both electricity and drinking water. The view of the system is given in Figure 6a. With a mathematical study, the Manzanares pilot plant is taken as a reference with a constant radiation intensity of 800 W/m2 and an ambient temperature of 27.2 °C. They claim that with the hybrid system, productivity increases and that they can obtain a system where both clean water and raw salt can be obtained economically. Ming et al. (2017) conduct a CFD study referencing the Manzanares pilot plant to desalinate seawater. They model a hybrid system that works with evaporation by spraying seawater at the chimney inlet. The visual of the system is given in Figure 6b. They show that as the amount of sprayed seawater increases, the effluent increases, and SCPP can be used for desalination. Rahbar and Riasi (2019) design a hybrid SCPP system with transparent PV cells integrated with the seawater desalination method, with mathematical modelling as shown in Figure 7. They use mathematical modelling in their study, where they reference the Manzanares pilot plant. They place a 3 cm high water layer on the floor of the system. They state that the power output of the SCPP system created with transparent PV will be 17.9% higher than the reference model. Similarly, they claim that the power output of the SCPP system with PV will be 31.3% higher than the system with PV+seawater desalination. Asayesh et al. (2017) develop a one-dimensional code for a hybrid SCPP system. With the code they developed, they work on desalination in the dimensions of the Manzanares pilot plant. They claim that the desalination system should be placed within 85-125 m radius from the collector inlet. Producing clean water by utilizing solar energy is currently more costly than fossil fuel-based systems (Zhang et al. 2018). However, it is very important to develop solar energy-based systems, carry out more experimental studies, and reduce costs.

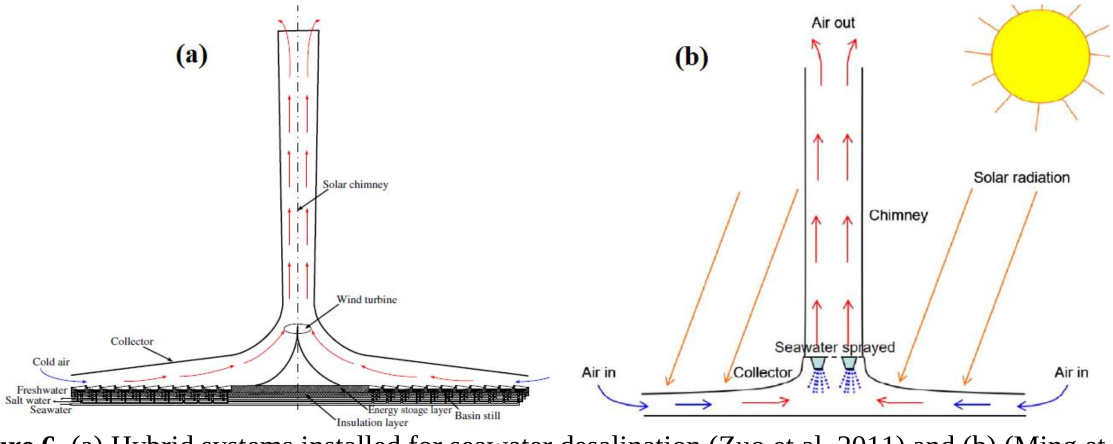

Figure 6. (a) Hybrid systems installed for seawater desalination (Zuo et al. 2011) and (b) (Ming et al. 2017).

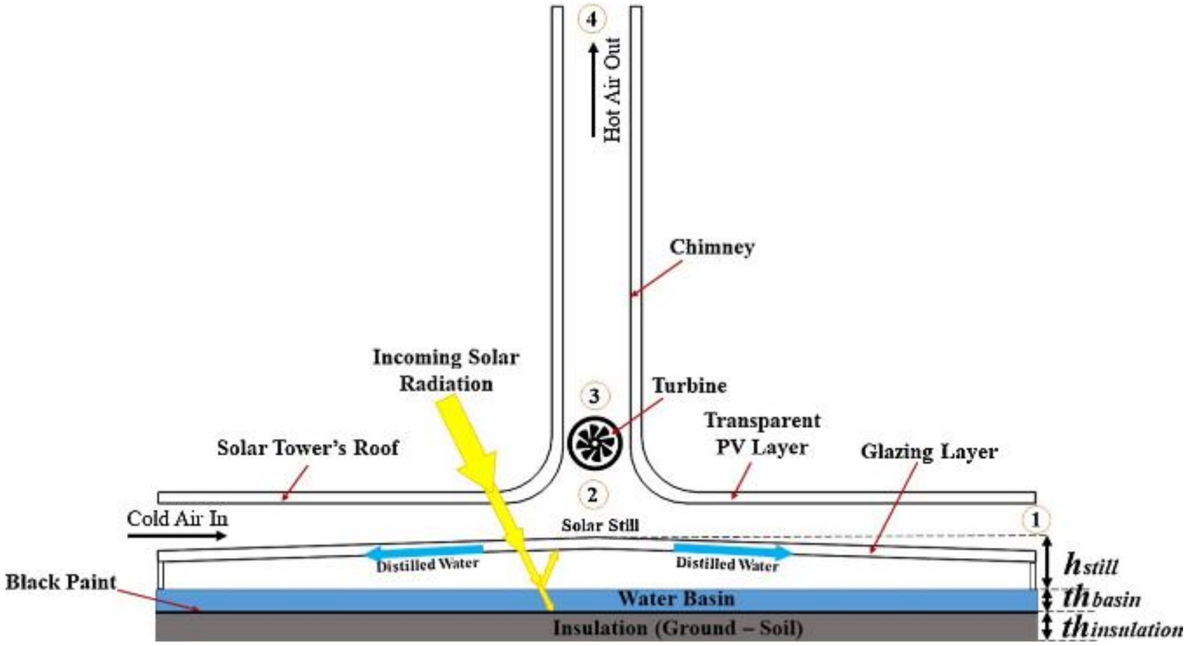

Figure 7. Hybrid SCPP system with transparent PV cell and integrated seawater desalination (Rahbar and Riasi, 2019)

3. Conclusion

SCPP systems are systems that can indirectly generate electricity from the sun. Although the low efficiency of the system is a major disadvantage, they can both increase performance and be used for different purposes with geometric configuration and hybrid systems. With the addition of PV modules to the system, the collector area can both serve as a cover for the system and provide additional energy. SCPP systems with a geothermal source can output power 24 hours a day. Similarly, waste heat from other systems can be used to achieve a greater temperature rise in the system air below the collector. SCPP systems can be used not only to generate electricity but also to obtain drinking water from seawater. Hybrid systems to be installed in this way can both increase the power output and obtain clean water. When the studies are examined, it is seen that the experimental examples are insufficient and mostly mathematical and CFD studies are carried out. Experimental studies should be increased to obtain more detailed data and to interpret the effectiveness of hybrid systems.

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