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A New Type of Hybrid Renewable Energies Power Plant with a Design for an Off-shore Location

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Abstract: This study introduces the concept of hybrid renewable energy power plants (HREPPs) which utilize various renewable energy sources to generate electricity. The solar chimney pond, air pumps, and underwater compressed air storage power plant (SCPAUPP) is a novel hybrid system designed for deployment in near-water areas. The SCPAUPP utilizes a solar chimney, solar pond, air pumps, and multi-level underwater compressed air energy storage to create an operational power plant capable of supplanting offshore fossil-fueled power plants. The governing equations of the SCPAUPP were derived and solved analytically, considering each subsystem as an independent entity and an integral part of the overall system. One of the primary benefits of SCPAUPP is its ability to store solar and wind energy through non-electric means, enabling enhanced control over power demand and supply without the need for large quantities of electrical batteries.The aim of this study is to demonstrate the limitations that arise from relying solely on a single renewable energy source instead of conventional fossil fuel power plants. However, the careful incorporation of a cohesive design tailored to a particular geographical area might improve the effectiveness of such replacement.To enhance comprehension of the potential of these systems, two case studies are presented. The objective of these case studies is to illustrate the complete spectrum of power generation options, encompassing both small-scale and large-scale scenarios. The small-scale power plant has a consistent daily power production ranging from 2.2436×10^3 (kWh) to 7.6229×10^3 (kWh), while the large-scale power plant has a daily power production ranging from 9.7191×10^6(kWh) to 65.753×10^6(kWh). The findings indicate that, with appropriate design and careful consideration of various factors, including economic and environmental concerns, these novel forms of renewable energy power plants have the potential to replace a portion of the existing fossil fuel-based power plants in the near future.

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1. Introduction

Small powers are usually neglected by human eyes. As a species, to gain power, we have always looked for strong enough sources to provide what we need. Furthermore, we have found an incredible one, fossil fuels. This tremendous energy gave us the power to dramatically change humans' lives in a relatively short period of time. It gave us the ability to do things that otherwise were impossible. However, every choice comes with a price; the price of dependency on a single power source alongside the irreversible fast destruction of the environment were the highest prices of this choice. Now that we are left at a point where we have hit the environment hard and nearly exhausted that energy source, we are looking for a powerful enough substitute to replace the current energy source fully. Although other types of power plants may be the primary power source in the future, all come with their own prices.

Transitioning to a low-carbon energy system is crucial for effectively addressing and combating the issues stemming from climate change. Transitioning to renewable energy such as solar and wind power necessitates a comprehensive strategy that takes into account market dynamics, legislative modifications, and the inherent characteristics of renewable energy sources. Formal modeling poses particular difficulties, especially in power markets, but it can also shed light on the competitive dynamics within the global energy market. The production patterns of capital-intensive renewable energy sources such as wind and solar depend on weather, posing significant investment risks. The trend towards renewable energy is undeniable, and there is continuous debate on the duration and exhaustion of fossil fuel reserves. Given the ongoing global transition towards renewable energy sources, it is imperative to tackle the obstacles related to the sporadic nature of wind and solar power. This requires innovative solutions such as advanced energy storage technologies to ensure a reliable and stable supply of electricity. Additionally, policymakers and industry leaders must carefully consider the long-term sustainability of fossil fuel supplies and explore alternative options to meet growing energy demands [1-3].

Thoroughly analyzing the environmental and economic effects of switching from fossil fuels to renewable energy sources is crucial. According to the study done by P. P. Edwards, V. L. Kuznetsov, W. I. David, and N. P. Brandon[4], fossil fuels—such as coal and natural gas—have historically dominated the energy supply. However, they are also linked to negative environmental effects such as significant CO2 emissions and air pollution[4].

In contrast, a more sustainable option with lower emissions and long-term viability is provided by renewable energy sources like solar and wind power [2].

An Environmental Impact Assessment (EIA) offers a methodical assessment of the ecological impacts associated with each energy source. The Economic Evaluation Function analyzes the economic factors, considering the past affordability of fossil fuels and their capacity to generate employment together with the expenses linked to the shift towards renewable energy sources [5]. Solarin in [6] conducted research on the impact of fossil fuel subsidies on environmental degradation in 35 emerging and developing countries. It discovered that a 10% increase in subsidies increases the ecological footprint by 0.3% to 1.5%. Population size, GDP per capita, urbanization, primary energy supply per capita, industrial share, resource rent, and globalization are all factors that contribute to environmental deterioration [6].

M. J. Saleh, F. S. Atallah, S. Algburi, and O. K. Ahmed in [7] analyze solar chimney power plant operational effectiveness and explore optimization methods like thermal storage, phase change materials, alternative technologies, external heat sources, and engineering design modifications. In [8]S. Yoo, S. Oh, and A. A. Hachicha explore the feasibility of a filter-equipped solar chimney power plant (FSCPP), combining SCPP and SALSCS components for dual air purification and power generation. N. Biswas, D. K. Mandal, S. Bose, N. K. Manna, and A. C. Benim in [9] explore the commercialization of solar chimney power plants (SCPPs), focusing on their sustainability and efficiency, while also recommending further research. Y. J. Choi, D. H. Kam, Y. W. Park, and Y. H. Jeong [10] developed an analytical model for a solar chimney power plant system with water storage under the collector to store the sun's energy and give it back to the system whenever the sun's radiation is unavailable. In the case study, we used the data given in [10] to validate the total efficiency of large and small-scale hybrid power plants.

Rao and Kaushika[11] developed an analytical model of a solar pond with a tube heat exchanger at the lower convection zone. Mori and Nakayama [12, 13] studied the heat transfer in the curved pipes, which led to a series of equations for Nusselt numbers in turbulent and laminar flows in curved pipes. Then, in [13], a practical approach was used to calculate the forced convection heat transfer in a spiral heat exchanger. Pourmokhtar and Khalilian in [14] conducted a parametric analysis of a solar pond in the weather environments of Orumieh.

This study introduces the concept of integrating the solar chimney and the solar pond as a means of storing solar energy through a non-electric process while distributing the generated power evenly across a 24-hour daily cycle. Combining these two systems was first introduced as a small prototype, built at the RMIT Campus in Bundoora. A. Akbarzadeh, P. Johnson, and R. Singh then [15] examined the potential benefits of combining a solar chimney with a solar pond toproduce power in salt-affected areas. Z. Z. Zhang, X. Liu, D. Zhao, S. Post, and J. Chen [16] explore New Zealand's wind energy sector restructuring, addressing cultural, environmental, and economic challenges, and evaluating seven storage technologies and small-scale household wind turbines' viability.

Regarding the underwater compressed air energy storages (UWCAES) that are employed for the non-electric storage of wind energy, specifically as compressed air energy storages, Wang, D. S.-K. Ting, R. Carriveau, W. Xiong, and Z. Wang [17] introduced an idea in which the UWCAES would use multiple accumulators at different depths to give the system a more flexible performance. Suppose the energy demand was insufficient to use the compressed air from the high-pressure storage at a depth of the ocean. In that case, the low-pressure storage could respond to the demand instead of the direct output of the power from the primary power plants [17]. The solar chimney literature was summarized in Table.1, and the solar pond/UWCAES literature was summarized in Tab.2.

Renewable energy sources such as sun, wind, wave and geothermal are among the most reliable sources on the Earth. Replacing fossil fuel sources with renewable energy sources is perhaps one of the most promising ideas for the future, although there are downsides to this idea. Two of the main problems with this idea can be named below:

- Neglecting the long-term consequences, relying solely on renewable energy sources rather than fossil fuels might potentially give rise to significant issues. Even though it seems that renewable energies are without waste and consequence to the environment in the short term, it is good to remember that the same thought went to fossil fuels at the start of their use.
- With fossil fuels, the ability to burn and use the energy at the desired time to sync the demand and supply of power accordingly is possible. However, with renewable energies, this ability is out of reach. Renewable energy systems must be designed to use the source at its peak, which is not always in sync with the supply and demand of the power. Then, we would only have two options to save it or not to use the maximum potential of the source.

Renewable energy power facilities face challenges in aligning supply and demand unlike fossil fuels. In order to optimize energy gain, it is important to do it at the point of maximum availability regardless of the idea whether it aligns with demand and supply schedules. This study aimed to tackle and resolve these issues using an innovative approach. Renewable energies are typically evaluated in isolation from fossil fuels, meaning that the transition from fossil-fueled energy to renewable energy is assessed using only a single type of renewable energy source. For example, most comparisons would be "one renewable energy source vs. fossil fuels." However, the problem with these types of comparisons is that maybe due to the locality of renewable energies, the fossil-fueled energies would always pull ahead and win the comparison.However, the overlooked point in this comparison is that every location has many different renewable energy sources. The comparison should be made between the energy derived from fossil fuels and the aggregate of renewable energy sources in that particular region. By implementing this alteration in the comparison, renewable energies may not be significantly lagging behind the competition. Nevertheless, due to the locality of the renewable energies, a specific design must be made for each region to reach the optimum point between different aspects of renewable energy sources such as the amount of power production, economics, and applicability of the power plants. The designs are specifically tailored for certain sites, aiming to maximize the utilization of renewable sources in order to optimize the aforementioned characteristics of the power plants. The objective of this study is to encourage the development of hybrid power plants that are specifically constructed for a particular location and maximize the utilization of renewable energy sources in that area with the intention of replacing existing fossil-fueled power plants. We call these power plants that use multiple renewable energy sources to generate electricity "hybrid renewable energy power plants" or "HREPP." These power plants must have two main characteristics:

- They use multiple renewable energy sources to generate power
- They consist of many smaller power plants that are cohesively put together so that there is solid reasoning for how they are arranged.

In the spirit of this study, a design for an HREPP that uses solar energy alongside the power of the wind and the ocean waves is represented. This hybrid power plant is presented for near-water locations and is placed off-shore. The introduced power plant is called "solar chimney pond, air pumps, and underwater compressed air storage power plant" or "SCPAUPP." This study aims to understand and analyze the potential of the HREPP by introducing an example of it (SCPAUPP) and by studying the SCPAUPP to know whether the HREPP is a good idea or not.

This study introduces the concept of the HREPPs as a novel approach to renewable energy generation, which has not previously been explored by other researchers. Furthermore, an exemplification of the HREPPs can be observed in the case of the study of SCPAUPP. This particular case has been thoroughly examined and analyzed as a representative example of the emerging category of modern power generation facilities introduced in this study. Additionally, we endeavored to address a primary challenge encountered in renewable energy power plants, namely the synchronization of demand and supply. One potential solution to address this issue involves the implementation of a non-electric storage system for renewable energies, which would enable the management and distribution of power at specific times as desired. In our pursuit to investigate various innovative strategies for incorporating renewable energy power plants, we introduced the groundbreaking concept of SCPAUPP. This study utilized MATLAB programming as a primary tool to effectively acquire and analyze the relevant data, hence improving the accuracy and dependability of our results. This study introduces several innovative concepts, including the integration of a solar pond, solar chimney, and air pump for power generation as well as the utilization of underwater compressed air energy systems (UWCAES) in combination with a hybrid power plant for non-electric power storage. These ideas aim to address the synchronization of demand and supply in the context of non-electric power storage.

2. Working Mechanism and Governing Equations of the SCPAUPP

Fig.1 presents a general schematic of the SCPAUPP with its subsystem's schematics and governing equations. In the figure the subsystems are (1) the chimney (2) the turbine (3) solar collector (4) spiral heat exchanger (5) the solar pond (6) wave energy converters (air pumps) which pump air straight to the system

(7) air pumps which pump air into the low-pressure storages (8) air ducts that guide the pumped air from air pumps under the turbine (9) air ducts that guide the stored air in UWCAES under the turbine (10) external turbines and solar panels that provide the energy of the compressors (11) low pressure compressed air storages (12) medium pressure compressed air storages (13) high pressure compressed air storages (14) air ducts that guide the compressed air to medium and high-pressure storages. The SCPAUPP consists of three main components:

- Solar chimney and solar pond combination system with spiral heat exchanger
- Wave energy converter (Air pumps)
- Multi-level underwater compressed air energy storage

2.1. Assumptions

The study employs a cylindrical coordinate system to analyze the solar pond system, centered at the origin and aligned with the midpoint of the hollow cylindrical duct at the apex. This coordinate system provides a pragmatic framework for understanding the complex dynamics of the hybrid system. The primary variables in the study demonstrate interdependencies along spatial axes, radial distance (r), azimuthal angle (θ), vertical height (z), time (t). To ensure coherence and conciseness, the study focuses on parameters and subscripts directly related to the solar pond's facets. This approach allows for accurate and concise equations tailored to individual research questions and objectives, while acknowledging the potential presence of additional elements and subscripts that do not significantly impact the specific phenomena being studied.

2.2. Solar Chimney and Solar Pond Combination System

The combination that we have introduced has the collector spreading through two main parts:

- The outer radius of the collector till the solar pond radius (area A): in this area, the collector is covering the base (ground), and the greenhouse effect would warm the air; thus, the air wants to have an updraft flow towards the chimney where a wind turbine would generate electricity.
- The inner radius of the collector (area B): the collector covers the solar pond in this area. Here, the solar energy would be absorbed by the blackened surface in the LCZ; thus, the greenhouse effect will not be as practical as before. Then, the stored energy would be transferred via two heat exchangers to the top layer underneath the turbine and would cause an updraft flow of air.

2.3. Wave Energy Convertor (Air Pumps)

To the best of the author's knowledge, no comparable concepts exist for the conversion of wave energy into an airflow that is subsequently utilized in a turbine to generate electricity. Nevertheless, it is sufficiently uncomplicated to assert that it has not eluded previous consideration. The system consists of a stationary chamber located beneath the SCPAUPP with a piston connected to a buoyant ball positioned on the water's surface. The ball moves in response to wave motion, causing air to be injected into the system. This airflow is subsequently utilized to power the turbine.

2.4. Modes of Operation of the UWCAES

Z. Wang, D. S.-K. Ting, R. Carriveau, W. Xiong and Z. Wang[17] developed a diagram in which four modes of operation were categorized based on power demands.This study presented eight modes of operation that utilize the same view. The solar chimney, solar pond combination, and air pumps were used when the required power exceeded the constant power generated, and these additional power demands were met through various modes of operation as:

Table 1: Previous research on solar chimneys studied in this work

History/paper	The subject of their study
Leonardo da Vinci [18]	Introduced the idea of the solar tower called a smoke jack.
Isodoro Cabanyes [19]	In 1903 offered to use the solar tower to generate electricity.
Gu¨nther [18]	In 1931, he introduced the first modern idea of the solar chimney, and in his studies, the power plant had a glass collector with a chimney running up a hill.
Prof.Bernard Dubos [18]	In 1926 presented, the idea of assembling a solar aero-electric power plant in North Africa with its chimney placed on the slope of a mountain.
W. Haaf, K. Friedrich, G. Mayr and J. Schlaich [20]	studied and discussed the basic principles of the experimental prototype built in Manzanares and compared the gathered data with the experimental data of the prototype
Mullett [18]	In 1987, a study showed that such a system's efficiencywas very low, and the only economical method of increasing it was to build a large-scale power plant.
Pasumarthi and Sherif [18]	In 1998, developed a mathematical model of the solar chimney power plant.
M. H. Ahmadi, O. Mohammadi, M. Sadeghzadeh, F. Pourfayaz, R. Kumar and G. Lorenzini[21]	In 2020 did an Exergy and economic analysis of solar chimneys in Iran's climate
X. Zhou, B. Xiao, W. Liu, X. Guo, J. Yang and J. Fan [22]	used a layer of seawater at the bottom of the SCPP that would vaporize and humidify the updraft air under the collector. Then, at the chimney's top, a high-efficiency condenser is placed at the outlet to condense the humid air, obtain the freshwater, and withdraw the dry air.
Niroomand and Amidpour [23]	used a humidification and dehumidification system (HD)at the entry of the collector to desalinate seawater

Table 2: The previous literature about solar pond / UWCAES studied in this paper

History/paper	The subject of their study
Von Kalecsinsky [24]	In the early 1900 discovered the solar pond idea by observing a natural solar pond.
M. Sodha, N. Kaushik and S. Rao[25]	Performed a thermal analysis on three zones of the solar pond
B. C. Cheung, R. Carriveau and D. S.-K. Ting [26]	Performed analysis on the parameters that affect the UWCAES
Z. Wang, D. S.-K. Ting, R. Carriveau, W. Xiong and Z. Wang [17]	Performed a conventional and advanced exergy analysis on the UWCAES
R. Carriveau, M. Ebrahimi, D. S.-K. Ting and A. McGillis[27]	Performed transient thermodynamic modeling of a UWCAES
B. C. Cheung, R. Carriveau and D. S. Ting [28]	did a multi-objective genetic algorithm optimization study on the design parameters of an underwater compressed air energy storage system

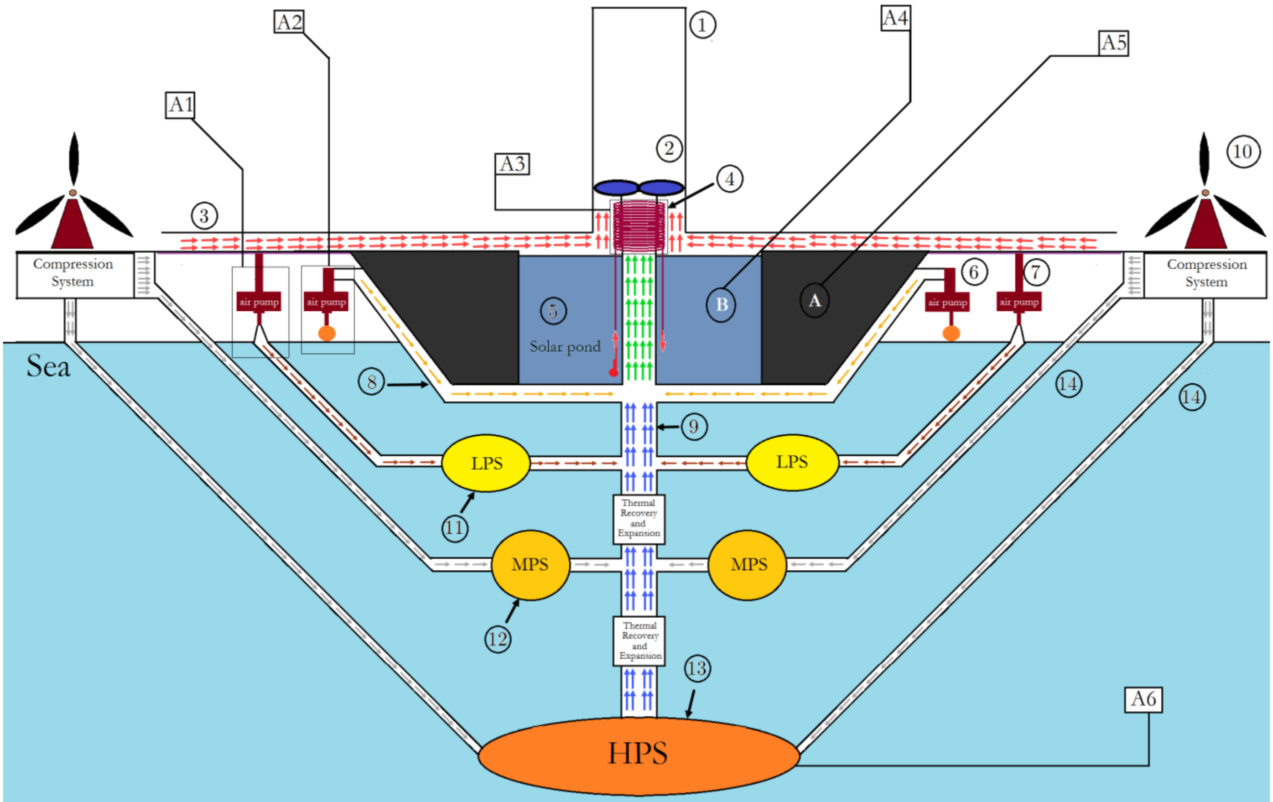
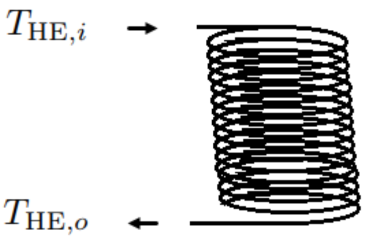
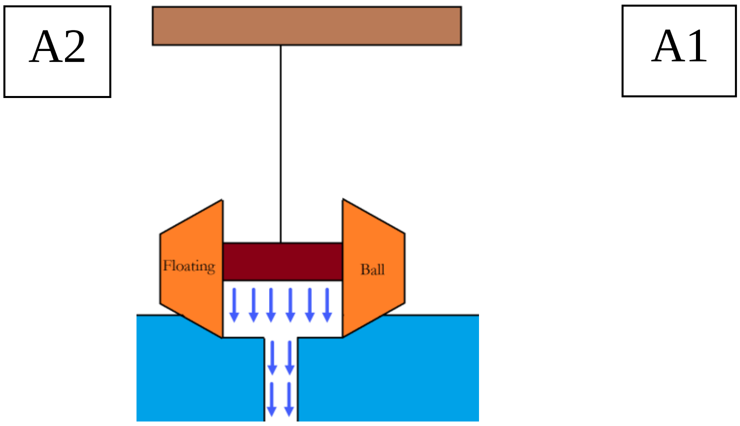


Fig. 1: General schematic of the SCPAUPP with its subsystem's schematics and its governing equations





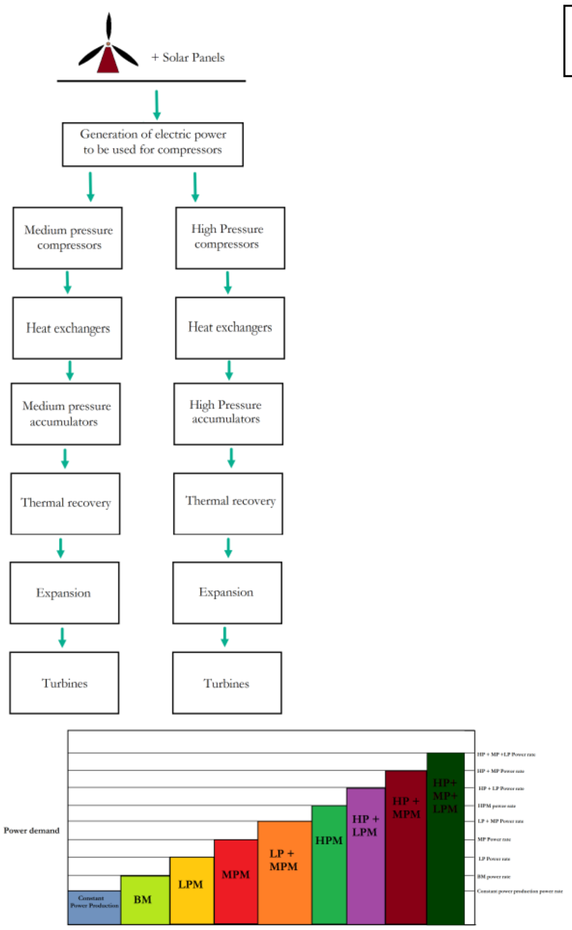
$$Q_{HE} = A_{wall}\left(T_{Wall(t)} - T_M\right)h_m$$

$$m_{injected} = \rho_a\left(\frac{\pi}{4}D^2_{Piston,ap}\right)\Delta L_{Piston,ap}$$

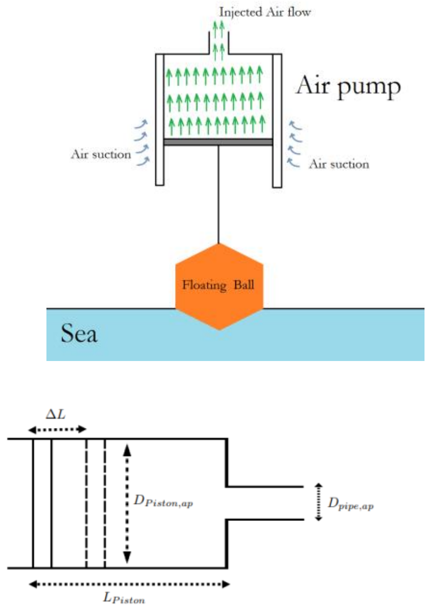
$$V_{avg,wave} = \frac{\Delta L}{\Delta t}$$

$$\dot{m}_{ap} = \rho_a\frac{\pi}{4}D^2_{Piston,ap}V_{avg,wave}$$

A6



A3



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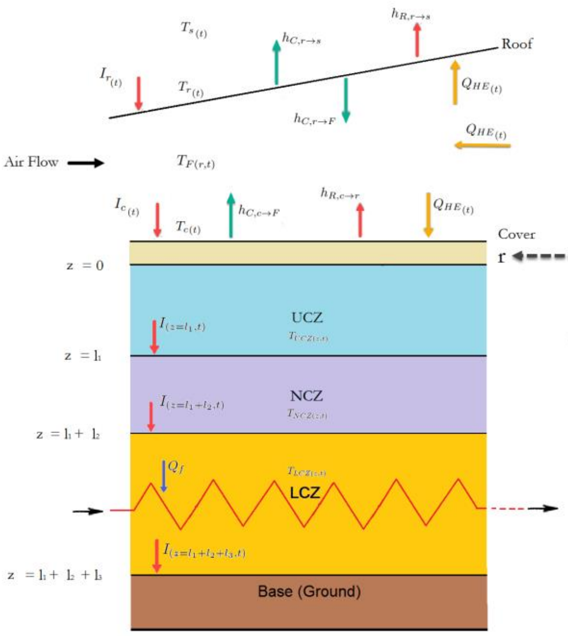


Area "B" roof:

$$\begin{aligned}&(I_{r(t)} + h_{R,\mathrm{UCZ}\to r}(T_{\mathrm{UCZ}(z=0,t)} - T_{r(t)}) + h_{R,\mathrm{NCZ}\to r}(T_{\mathrm{NCZ}(z=l_1+l_2,t)}\\ &\qquad - T_{r(t)})\\ &+h_{R,\mathrm{LCZ}\to r}(T_{\mathrm{LCZ}(z=l_1+l_2+l_3,t)} - T_{r(t)})) \times A_{pond} + Q_{\mathrm{HE}(t)}\\ &= \left(h_{C,r\to s}\left(T_{r(t)} - T_{s(t)}\right) + h_{C,r\to F}\left(T_{r(t)} - T_{F(r,t)}\right)\right.\\ &\qquad \left. + h_{R,r\to s}\left(T_{r(t)} - T_{s(t)}\right)\right) \times A_{pond}\end{aligned}$$

Air under area "B":

$$\begin{aligned}&\left(h_{C,r\to F}\left(T_{r(t)} - T_{F(r,t)}\right) + h_{C,c\to F}\left(T_{\mathrm{UCZ}(z=0,t)} - T_{F(r,t)}\right)\right) \times A_{pond}\\ &\qquad + Q_{\mathrm{HE}(t)} = \dot{m}_F c_{pF} \frac{\Delta T_{F(r,t)}}{\Delta r}\end{aligned}$$

UCZ:

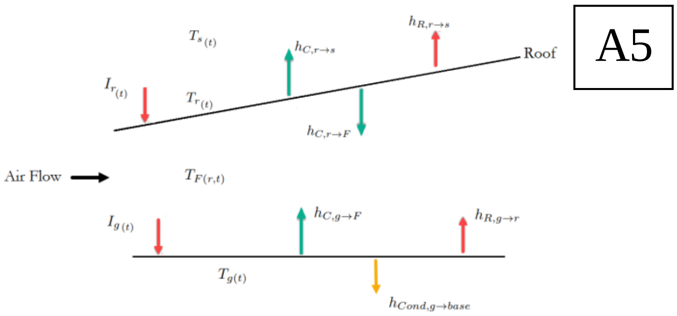
$$\begin{aligned}I_{(z=0,t)} + Q_{\mathrm{HE}(t)} = I_{(z=l_1,t)} &+ h_{C,\mathrm{UCZ}\to F}\left(T_{\mathrm{UCZ}(z=0,t)} - T_{F(r,t)}\right)\\ &+ h_{R,\mathrm{UCZ}\to r}\left(T_{\mathrm{UCZ}(z=0,t)} - T_{r(t)}\right)\\ &+ h_{R,\mathrm{NCZ}\to r}\left(T_{\mathrm{NCZ}(z=l_1+l_2,t)} - T_{r(t)}\right)\\ &+ h_{R,\mathrm{LCZ}\to r}\left(T_{\mathrm{LCZ}(z=l_1+l_2+l_3,t)} - T_{r(t)}\right)\\ &+ h_{\mathrm{UCZ}\to F}\left(T_{\mathrm{UCZ}(z,t)} - T_{F(r,t)}\right)\\ &+ h_{F\to \mathrm{UCZ}}\left(T_{\mathrm{UCZ}(z,t)} - T_{(z=l_1,t)}\right)\\ &+ h_{evap}\left[\left(T_{\mathrm{UCZ}(z,t)} - \gamma_F T_{F(t)}\right)2.933\right.\\ &\left.- 39.11505(1 - \gamma_F)\right] + \rho_{cw} l_1 \frac{\mathrm{d}T_{\mathrm{UCZ}(z,t)}}{\mathrm{d}t}\end{aligned}$$

NCZ:

$$h_{Cond,\mathrm{NCZ}} \frac{\partial^2 T_(z,t)}{\partial z^2} = \rho_{\mathrm{NCZ}} c_{p,\mathrm{NCZ}} \frac{\partial^2 T_{(z,t)}}{\partial t^2} + \frac{\partial I_{(z,t)}}{\partial z}$$

LCZ:

$$\begin{aligned}Q_f = -h_{Cond,\mathrm{NCZ}} \frac{\partial T_{(z,t)}}{\partial z}\Big|_{z=l_1+l_2} &- h_{R,\mathrm{LCZ}\to \mathrm{NCZ}}\left(T_{\mathrm{LCZ}(z=l_1+l_2+l_3,t)} - T_{avg,\mathrm{NCZ}(t)}\right)\\ &- \rho_{cw} l_3 \frac{\mathrm{d}T_{LCZ(t)}}{\mathrm{d}T} + I_{(z=l_1+l_2,t)}\\ &+ h_{Cond,g} \frac{\partial T_{z,t}}{\partial z}\Big|_{z=l_1+l_2+l_3}\end{aligned}$$



Area "A":

$$I_{r(t)} + h_{R,g\to r}(T_{g(t)} - T_{r(t)}) = h_{C,r\to s}(T_{r(t)} - T_{s(t)}) + h_{C,r\to F}(T_{r(t)} - T_{F(r,t)}) + h_{R,r\to s}(T_{r(t)} - T_{s(t)})$$

Fig. 1 continued

- Battery mode(BM): when the power demand is less than the rated power of the LPS, the demanded power would directly be used from the main power plant or the stored electric power in the batteries. Because the solar chimney, solar pond combination system, and air pumps constantly generate power, this combination is called a "constant power production system."
- Low-pressure mode (LPM): when the demanded power is between the LPS andMPS-rated power, the non-compressed air is released from the LPS, and the remaining demanded power is supplied by the electric power stored in the batteries.
- Medium pressure moden (MPM): when the demanded power is between the rated power of the MPS and the sum of the rated power of MPS and LPS. The compressed air from the MPS would be released after thermal recovery and expansion, creating the airflow which would supply most of the demanded power. The remaining demanded power would be supplied from the electric power stored in the batteries.
- Low plus Medium pressure mode (LP+MPM): it describes the situation when the demanded power is between the rated power of the sum of MPS and LPS and the rated power of HPS in this mode. First, the compressed air from MPS would be released. After thermal recovery and expansion, the non-compressed air from the LPS would be released, creating the airflow that would supply most of the demanded power; the remainingpower would be supplied by the electric power stored in thebatteries.
- High-pressure mode (HPM): when the demanded power is between the rated Power of the HPS and the sum of the rated Power of HPS and LPS, the compressed air from the HPS is released after thermal recovery and expansion and creates the airflow, which would supply most of the demanded power. The remaining demanded power would be supplied from the electric power stored in the batteries.
- High plus Low-pressure mode (HP+LPM): when the demanded power is between the HPS-rated power and the sum of the LPS and HPS-rated power, the compressed air is released from the HPS. After thermal recovery and expansion, the non-compressed air from the LPS would be released, and it would create the airflow which would supply most of the demanded power and the remaining demanded power would be supplied by the electric power stored in thebatteries.
- High plus Medium pressure mode (HP+MPM): when the demanded power is between the sum of HPS and LPS rated power and the sum of the MPS and HPS rated power, the compressed air would be released from the HPS, and after thermal recovery and expansion, the compressed air from the MPS would be released; after thermal recovery and expansion, it would create the airflow which would supply most of the demanded power, and the remaining demanded power would be supplied by the electricpower stored in the batteries.
- High plus Medium plus Low-pressure mode (HP+MP+LPM): when the demanded power is between the sum of HPS and MPS rated power and the sum of the LPS and MPS, and HPS rated power, the compressed air would be released from the HPS; after thermal recovery and expansion, the compressed air fromthe MPS would be released; after thermal recovery and expansion, the non-compressed air from the LPS would be released. It would create the airflow which would supply most of the demanded power and the remaining demanded power would be supplied by the electric power stored in the batteries.

2.5. Ideas that can Improve the SCPAUPP

2.5.1. Floating Solar Chimney

The primary concern associated with a functional solar chimney pertains to the expenses and the process of constructing the chimney structure. Several strategies could be employed to decrease this expense such as using geographical advantages to minimize costs and facilitating the construction or integration of an existing tall structure with the solar chimney to mitigate the overall cost of the chimney. Nevertheless, there exists a concept for the implemented hybrid system that would significantly decrease the construction expenses and streamline the construction procedure. Papageorgiou offered floating chimney. The chimney is built using flexible material instead of concrete, and it would float with the help of gases lighter than air such as helium. The support rings are made in a way that would let the air flow pass freely so that the chimney would not fail under wind pressure. Due to the fundamentals of this design, it weighs much less than concrete, which is a huge advantage considering the hybrid power plant is placed on water [29].

2.5.2. Water Desalination System

Prior research has put up many approaches to integrate the solar chimney with the seawater desalination system. Two of these combinations can be used for the SCPAUPP. The first system was proposed by X. Zhou, B. Xiao, W. Liu, X. Guo, J. Yang, and J. Fan. [22] used a layer of seawater at the bottom of the SCPP that would vaporize and humidify the updraft air under the collector. Then, at the chimney's top, a high-efficiency condenser is placed at the outlet to condense humid air, to obtain fresh water, and to withdraw dry air. The second method proposed by Niroomand and Amidpour [23] would use a humidification and dehumidification system (HD) at the entry of the collector.

3. Power Production of the Hybrid System

3.1. Total Power Generation of the Hybrid System

The total power generated by the hybrid system is the sum of the three mainsubsystems:

- Solar chimney(sc):
  - Power output due to the greenhouse effect caused by the collector
    - Power output due to the heat load given to the subsystem from the spiralheat exchanger
- Wave energy converter or air pump(ap)
- Air storage units

Hence, the power production of the power plant can be calculated as follows:

$$Power_{SCPAUPP} = Power_{sc} + Power_{ap} + Power_{storages} \quad (1)$$

There are two main methods of calculating the power production of each subsystem:

- Direct method: in this method, the power produced by the subsystem is calculated using the mass flow rate of air entering the turbine and the driving force of that air.
- Indirect method: in this method, the power produced by the subsystem is calculated using the energy balance equation alongside the efficacy of each relatedcomponent.

3.2. Direct Method

The key to calculating the power production of the hybrid power plant using the direct method is the mass flow of the air passing through the turbine. Three different sources can create airflow under the turbine:

1. Mass flow rate produced by solar chimney mechanism
2. Mass flow rate produced by wave energy converter
3. Mass flow rate produced by storage

$$\dot{m}_{passing\ through} = \dot{m}_{sc} + \dot{m}_{ap} + \dot{m}_{storages} \quad (2)$$

Moreover, an important point to consider is that all these mass flow rates would have their flow areas, which should be considered while calculating the power generation of the power plant. To ease the calculation of the flow areas, the' RFA' was introduced. RFA shows the percentage of the chimney's zone that each source of mass flow rates would occupy, and it can be calculated as:

$$RFA = \frac{A_{Flow\ area}}{A_{chimney}} \quad (3)$$

As mentioned by [10], the power generated by each mass flow rate is dependent on four parameters:

1. The efficiency of the wind turbine
2. The mass flow area
3. the velocity of air flow
4. The driving force of each air flow

And the Eq.(4) shows the relation of these parameters [3]:

$$Power = \eta_{turbine} \times A_{chimney} \times RFA \times \Delta P \times V \quad (4)$$

3.3. Indirect Method

In this method, the main idea is that the input power must be equal to the output power derived from the conservation of the energy law. Thus, we can write the equation for each subsystem as:

$$Power = \eta_{turbine} \times A_{chimney} \times RFA \times \Delta P \times V \quad (4)$$

$$Output\ Power = Input\ power \times efficiency \quad (5)$$

The power output of each subsystem is given in Table 3.

Table 3: Power output of each subsystem of the SCPAU

Subsystem	Description	Governing equations
Collector	Convergence method (Direct method): To calculate the mass flow rate of the solar chimney due to the collector's energy gain, we have to use a convergence loop using the heat transfer equations to find the numeric solution to the mass flow rate problem, then use the mass flow rate to find the velocity of the airflow passing through the turbine then use Eq.(6) to calculate the power output due to the greenhouse effect caused by the collector.[30]	$\mathrm{Power}_{Collector} = \eta_{\mathrm{turbine}} \times A_{chimney} \times \mathrm{RFA}_{sc} \times \Delta P_{sc} \times V_{sc}$ (6)
	Maximum power output equation(Indirect method): Ming[30], in chapter three, represented a direct method of calculating the solar chimney's power output and mass flow rate using the chimney's geometry and air density outside and inside.	$\mathrm{Power}_{Max,Collector} = \frac{\rho_{o,air}}{\rho_{i,air}} \frac{g}{C_{P,air} T_{s(t)}} H_{ch} \times \left(A_{\mathrm{AreaA}} \times I_{r(t)}\right)$ (7)
Heat exchanger	Direct method: Considering Eq.(7) can be written as the equation in the way that the primary source of energy gain would come from the spiral heat exchanger[13]	$\mathrm{Power}_{Max,HE} = \frac{\rho_{o,air}}{\rho_{i,air}} \frac{g}{C_{P,air} T_{s(t)}} H_{ch} \times (Q_{HE})$ (8)
Air pumps	Direct method	$\mathrm{Power}_{ap} = \eta_{\mathrm{turbine}} \times A_{chimney} \times \mathrm{RFA}_{ap} \times \Delta P_{ap} \times V_{ap}$ (9)

Subsystem	Description	Governing equations
UWCAES	Direct method	$\text{Power}_{st} = \eta_{\text{turbine}} \times A_{ch} \times \text{RFA}_{st} \times \Delta P_{st} \times V_{st}$ (10)
	Indirect method: In this method, round-trip efficiencydetermines how much energy can be regained from the system. Round-trip efficiency can be described as retainable energy after storing it.[31]	$\eta_{\text{round-trip}} = \frac{Power_{discharge} \times t_{discharge}}{Power_{charge} \times t_{charge}}$ (11)

4. Case Study

4.1. Input Data

In this case study, the power production rate of two hypothetical SCPAUPP was estimated, one on a small scale and another on a large scale for the average hottest day of the year (July 21) for a location with a latitude of 50.8°E. The input data of both small and large-scale SCPAUPP is given in Table 4, and the assumptions made for the analysis are presented below:

- The calculated temperature and global solar radiation for July 21in a location with a latitude of 50.8°E are shown in Fig.3. The hourly temperature is estimated using a linear interpolation of 10 existing data.
- For the outlet temperature of the tube heat exchanger, an estimate derived from already existing data from [11] and a correction factor for each hour of the day was used. The data shown in [11] is for New Delhi 1974, and the needed data is for July 21in a location with a latitude of 50.8°E. To calculate the correction factor, two sub-factors are required: one for the correction of the hourly temperature difference and another for the hourly solar radiation difference. Then, the primary correction factor for each hour can be derived by averaging the two sub-factors. The sub-factor (A), sub-factor (B), and main correction factor equations are shown in Eq. (12), (13), and (14), respectively.

$$CF_A = \frac{\text{hourly radiation at } 50.8\,\square\ \text{E}}{\text{NewDelhi'shourlyradiation}} \tag{12}$$

$$CF_B = \frac{\text{the hourly temperature at } 50.8\,\square\ \text{E}}{\text{NewDelhi's hourly temperature}} \tag{13}$$

$$CF = \frac{CF_A + CF_B}{2} \tag{14}$$

- The heat transfer from the heat exchanger to the air under the turbine is doneby assuming an average of 40° C of a uniform wall temperature.
- The total efficiency of the two small and large-scale SCPAUPP is derived from validating the datawith the study done by Y. J. Choi, D. H. Kam, Y. W. Park, and Y. H. Jeong[10].

4.2. The Matter of Compressed Air Storages

The amount of compressed air inserted as an input in Table 4 for both small and large-scale SCPAUPP is enormous and, with current technology, is nearly impossible to achieve. It was not put this way to force the system to yield more power, but it was put there to show the potential of this SCPAUPP and, eventually, the potential power production that HREPP can have. This assumption might be improbable now, but very shortly, it would be possible considering the rate of progress made in sciences in the past decade and knowing that the efficiency of compressors is low compared to other equipment.

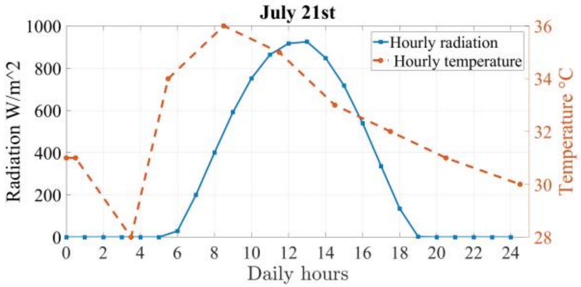
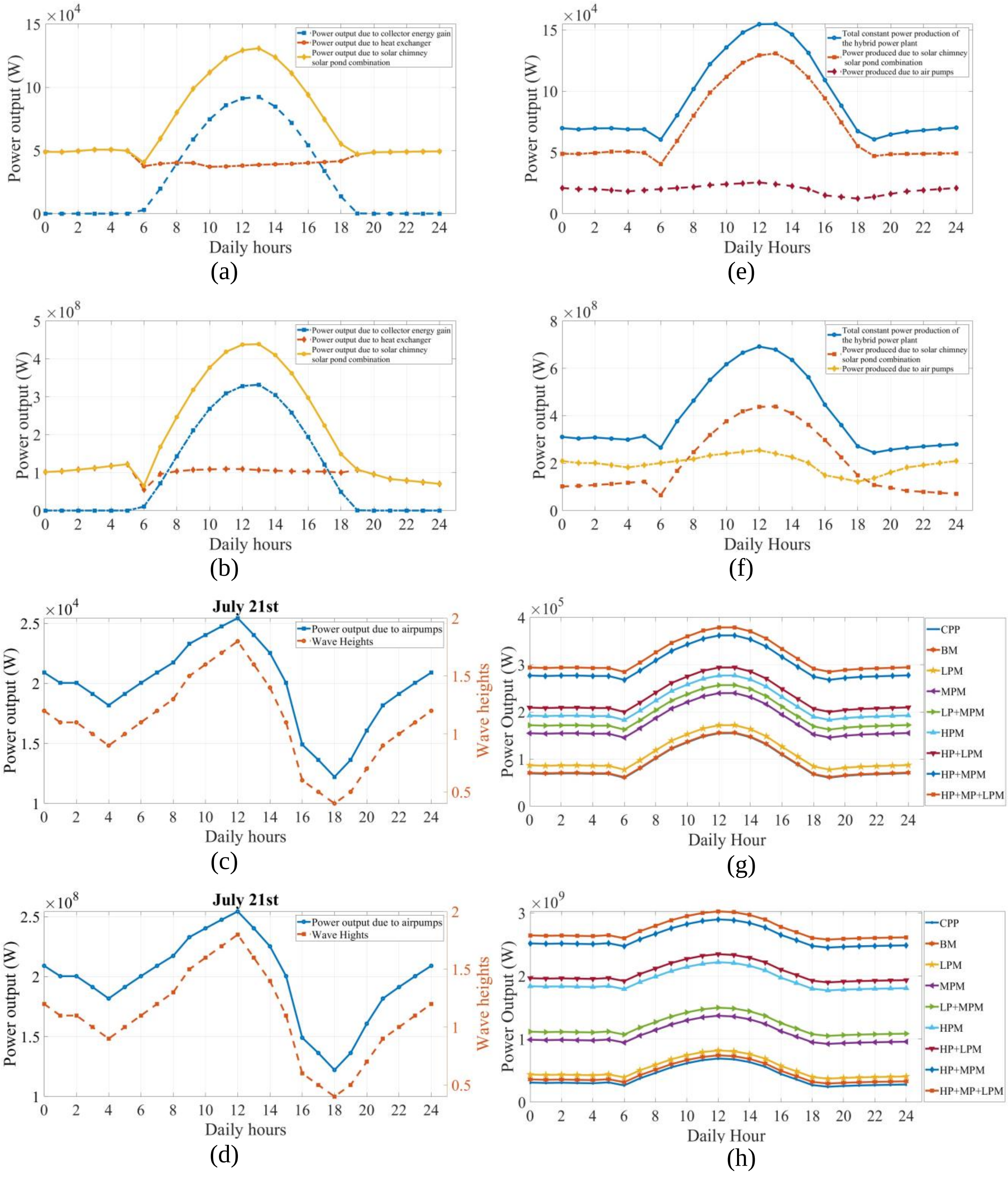


Fig. 3: Hourly solar radiation and temperature of July 21, 2019, 50.8°E

Table 4: Small-scale and large-scale SCPAUPP geometries

Small scale parameters	Values	Large scale parameter	Values
$H_{chimney}$	100 m	$H_{chimney}$	1000 m
R_r	150 m	R_r	4500 m
R_{pond}	50 m	R_{pond}	1500 m
$R_{chimney}$	10 m	$R_{chimney}$	100 m
RFA_{sc}	0.5	RFA_{sc}	0.5
η_{total}	0.5	η_{total}	0.2
R_{curv}	6.5 m	R_{curv}	55 m
R_{HE}	0.1 m	R_{HE}	0.5 m
$R_{ap,piston}$	10 m	$R_{ap,piston}$	10 m
RFA_{ap}	0.15	RFA_{ap}	0.15
$N_{HE,turns}$	40	$N_{HE,turns}$	10000
Z_{LPS}	50 m	Z_{LPS}	50 m
$Volume_{LPS}$	2000 m^3	$Volume_{LPS}$	1500000 m^3
T_{LPS}	298.15 k	T_{LPS}	298.15 k
Z_{MPS}	200 m	Z_{MPS}	200 m
$Volume_{MPS}$	2500 m^3	$Volume_{MPS}$	20000000 m^3
T_{MPS}	296.15 k	T_{MPS}	296.15 k
Z_{HPS}	600 m	Z_{HPS}	600 m
$Volume_{HPS}$	1200 m^3	$Volume_{HPS}$	1500000 m^3
T_{HPS}	283.15 k	T_{HPS}	283.15 k



(a) (e)

(b) (f)

(c) (g)

(d) (h)

Fig.e 4: (a, b) small-scale and large-scale solar chimney solar pond combination power output (c, d) small-scale and large-scale air pumps power output (e, f)small-scale and large-scale total constant power output (g, h) small-scale and large scale UWCAES modes of operations

Table 5: The maximum, minimum, total daily, and average hourly power production of the smallscale SCPAUPP

Small scale SCPAUPP	Maximum(kW)	Minimum(kW)	Total daily(kWh)	Average hourly(kWh)
Heat exchanger	50.629	37.046	1.0492×10^{3}	43.720
Collector	92.168	0	7.2249×10^{2}	30.103
Air pump	12.915	55.059	4.7189×10^{2}	19.662
Solar systems combination	13.077	40.397	1.7717×10^{3}	73.824
Constant power production	15.479	60.431	2.2436×10^{3}	93.486

Table 6: The maximum, minimum, total daily, and average hourly power production of the large scale SCPAUPP

large scale SCPAUPP	Maximum(kW)	Minimum(kW)	Total daily(kWh)	Average hourly(kWh)
Heat exchanger	1.2214×10^{5}	0.5462×10^{5}	2.3992×10^{6}	0.9997×10^{5}
Collector	3.3180×10^{5}	0	2.6009×10^{6}	1.0837×10^{5}
Air pump	4.3745×10^{5}	1.4882×10^{5}	4.7189×10^{6}	1.9662×10^{5}
Solar systems combination	4.3868×10^{5}	6.5018×10^{5}	5.0002×10^{6}	2.0834×10^{5}
Constant power production	6.9176×10^{5}	2.4419×10^{5}	9.7191×10^{6}	4.0496×10^{5}

Table 7: The UWCAES power production for the small-scale SCPAUPP

small scale SCPAUPP	Maximum(kW)	Minimum(kW)	Total daily(kWh)	Average hourly(kWh)
BM	1.5579×10^{2}	0.6143×10^{2}	2.2676×10^{3}	0.9448×10^{2}
LPM	1.7177×10^{2}	0.7741×10^{2}	2.6512×10^{3}	1.1046×10^{2}
MPM	2.3969×10^{2}	1.4533×10^{2}	4.2812×10^{3}	1.7838×10^{2}
LPMPM	2.5668×10^{2}	1.6231×10^{2}	4.6888×10^{3}	1.9536×10^{2}
HPM	2.7705×10^{2}	1.8268×10^{2}	5.1778×10^{3}	2.1574×10^{2}
HPLPM	2.9403×10^{2}	1.9966×10^{2}	5.5853×10^{3}	2.3272×10^{2}
HPMPM	3.6195×10^{2}	2.6758×10^{2}	7.2154×10^{3}	3.0064×10^{2}
HPMPLM	3.7893×10^{2}	2.8456×10^{2}	7.6229×10^{3}	3.1762×10^{2}

Table 8: The UWCAES power production for the large-scale SCPAUPP

Large scale SCPAUPP	Maximum(kW)	Minimum(kW)	Total daily(kWh)	Average hourly(kWh)
BM	0.7418×10^{6}	0.2950×10^{6}	1.0919×10^{7}	0.4549×10^{6}
LPM	0.8191×10^{6}	0.3715×10^{6}	1.2775×10^{7}	0.5323×10^{6}
MPM	1.3709×10^{6}	0.9234×10^{6}	2.6020×10^{7}	1.0841×10^{6}
LPMPM	1.4983×10^{6}	1.0507×10^{6}	2.9076×10^{7}	1.2115×10^{6}
HPM	2.2200×10^{6}	1.9331×10^{6}	4.6396×10^{7}	1.93×10^{6}
HPLPM	2.3473×10^{6}	1.8997×10^{6}	4.9452×10^{7}	2.0605×10^{6}
HPMPM	2.8991×10^{6}	2.4516×10^{6}	6.2697×10^{7}	2.6123×10^{6}
HPMPLM	3.0265×10^{6}	2.5789×10^{6}	6.5753×10^{7}	2.7397×10^{6}

Table 9: Range of power production of the different types of power plants according to [32]

	Small scale power Plant (MWH/Day)	Large scale power Plant (MWH/Day)
Hydropower plant	0.12	150000
Coal power plant	1600 (Kahone powerplant inSengal)	85000 (Taichung power plant in Taiwan)
Geothermal power plant	700 (Italy's San Martino power plant)	23000 (Geyser's site in the USA)
Onshore wind farm	80 (Utgrunden power plant in Sweden)	24000 (Gansu wind farm inChina)
Off-shore wind farm	70(Mt. Stuart Wind Farm in New Zealand)	6800 (UK's London Array)
Photovoltaic (PV) farm	48 (Jarqavie, Iran)	7200 (Tengger Desert solar park in China)
SCPAUPP	7.623 (Small-scaled case study SCPAUPP)	65753 (Large-scale case study SCPAUPP)

Table 10: The average population coverage of the introduced hybrid power plant around the world

A person power consumption	Peryear (kWh/year)	Perday (KWh/day)	Average populationcoverage	
			Small scale	Large scale
SA	12487	34.21	222	1922040
Canada	16373	44.85	169	1466060
Australia	9580	26.24	290	2505830
Russia	7507	20.56	370	3198100
China	5858	16.05	474	4096760

5. Results and Discussion

The plot results for small and large-scale SCPAUPP are given in Fig.4. The power generated by the collector energy gain demonstrates a noteworthy pattern throughout the duration of a day as depicted in Fig. 4 (a and b). In instances where sunlight is absent, the power output of the system diminishes to zero that signifies that solar energy serves as the predominant catalyst for its operation. On the other hand, when the sun is at its zenith, the power generation from the collector energy gain, likewise, reaches its maximum. The observed dynamic behavior serves as an evidence for the system's dependence on solar radiation. Besides, the power generated by the heat exchanger exhibits a higher degree of consistency as it is able to maintain a stable level of output over the course of the day. The observed continuous power generation highlights the heat exchanger's ability to maintain its operational efficiency, despite fluctuations in solar radiation. The combination of these two components produces a composite power output that displays unique characteristics. It maintains a steady level of electricity generation throughout the day. As the morning advances and solar irradiance intensifies, the power output exhibits a gradual and continuous increase, culminating in its maximum value around midday. Following this, as the sun initiates its descent, there is a gradual decrease in power output ultimately leading to a return to the previously established baseline. The utilization of a dual-component system enhances the dependability and uninterrupted generation of energy by effectively capitalizing on the respective advantages of the collector and heat exchanger. This approach ensures harmonized energy production throughout the entirety of the day. Upon analysis of Fig. 4 (c and d), a conspicuous correlation becomes evident, illustrating the direct association between the power output of the air pump and the prevailing wave heights. The figures presented demonstrate a positive correlation between wave heights and the power output of the air pump.The combination of air pumps and solar systems, as depicted in Figure 4 (e and f), presents a compelling viewpoint on the collective energy generation potential of the solar chimney and solar pond. The presented figure provides compelling evidence that the integrated system is capable of maintaining a consistent baseline of power production. Throughout the course of the day, the hybrid system demonstrates a gradual escalation in power generation, culminating in its peak performance during the midday hours. The midday peak corresponds to the time of day when solar radiation and wave heights tend to reach their maximum values, indicating the combined impact of utilizing both solar and wave energy conversion technologies. After reaching its highest point during midday, there is a discernible decrease in power generation, mirroring the inherent patterns of the sun's descent and the subsequent reduction in wave activity. The decline in power is characterized by a gradual and progressive decrease, ultimately resulting in the system returning to its initial established baseline. The capacity of the Underwater Compressed Air Energy Storage (UWCAES) system to consistently generate power while adjusting to fluctuations in power supply and demand is effectively demonstrated through the depiction of the eight modes of operation, as illustrated in Figure 4 (g and h). The depicted methods of operation offer a structured and flexible approach to power generation. The presented figures provide clear evidence of the UWCAES system's capability to seamlessly transition between different operational modes. Each mode is distinguished by a discernible and gradual rise in power generation. The progressive pattern observed in the system illustrates its ability to adapt and exhibit flexibility in its response to fluctuations in power supply and demand. The modes mentioned above serve as a versatile tool for modifying the power output in order to align with the specific requirements of the energy grid or consumer demand. The UWCAES system effectively ensures a consistent provision of electricity and improves its capacity to accommodate changes in the energy industry through the implementation of incremental adjustments to power generation. The importance of UWCAES as a reliable and flexible component within an integrated energy generation and storage system is emphasized by this capability, thereby improving the stability and efficiency of the power infrastructure.

Tables 5 and 6 provide a comprehensive breakdown of the maximum, minimum, and total daily power production as well as the average hourly power production for the constant power production system. The primary objective of these tables is to provide a clear representation of the power generation capacity of the hybrid power plant. Furthermore, Tables 7 and 8 contain a comprehensive list of the eight modes of operation and their corresponding parameters.

Table 9 presents a comprehensive analysis of power generation derived from diverse power plants, incorporating real-world instances from different global regions. The data utilized in this table has been obtained from a reliable source, referenced as [32]. The presented table showcases the extensive range of power generation capacities, thereby illustrating the diverse energy requirements and available resources on a global scale. Furthermore, it provides valuable insights regarding the potential power generation capabilities of the SCPAUPP that has been introduced. Table 10 displays the global average population coverage of the introduced hybrid power plant. This dataset considers the variations in power consumption behaviors among different regions and countries. The remark underscores the SCPAUPP's capacity to accommodate different population proportions, hence showcasing its promise as a scalable and flexible option for meeting energy needs in various regions. The critical elements of SCPAUPP can be summarized as follows:

- Combining the solar chimney and solar pond in the described manner can be helpful for two main reasons; first, it can expand the time range in which the power is presented into the system, which is over 24h instead of instantaneous use. Furthermore, the second reason is that it allows us to store energy in a manner that is under our control.
- Wave energy converters, with the help of the proper piping, can be used to pump air into the main lines, so only one turbine would be used to generate power.
- The eight modes of operation give the hybrid power plant a wide range of flexibility over the syncing power of the system with the demanding power.

The primary objective of this work was to investigate the potential of HREPP as a viable solution for future power generation. In this section, the outcomes of the case study were examined to determine the utility of this SCPAUPP. Additionally, if this SCPAUPP proves to be a helpful replacement for fossil-fueled power plants, it can be said that with the right design, the HREPP can be a good idea for future power plants. The pros and cons of the SCPAUPP can be summarized as follows:

Pros:

1. Small step increases in power production give us a better control over syncing the supply and the demand for power.
2. In theory, it would emit no harmful gas into the environment after the completion of the production of the system.
3. The average hourly power production is almost midway between the maximum and minimum power production, and the gap between them is not that huge, which gives a more uniform power distribution over 24h daily cycle.
4. This type of power plant can have a vast range of power production depending on its scale (maybe a range as extensive as hydropower plants).

Cons:

1. The scale of land needed to build this SCPAUPP is huge; thus, not only would it take a relatively ample space, but it also may increase the energy loss due to the need for the long pipes.
2. Because the power production is discrete, the battery packs are required to store the remaining energy.
3. The SCPAUPP can only be placed on large bodies of water
4. according to [33], the time of most power consumption in a household is between 13:00 To 21:00. Besides, the SCPAUPP would have the most power production in the hours of 8:00 to 16:00. Thus, between 16:00 and 21:00, the power demand and supply would be out of sync if the primary source of consumption were households.

6. Conclusion

This study aimed to introduce an HREPP that uses renewable energy sources to produce power. The critical points of this paper can be summarized below:

- It is a new idea that can take advantage of as many renewable energy sources as possible.
- This idea can compete with its equivalent rival of the fossil-fueled power plant.
- SCPAUPP was an example of how combining multiple renewable energy systems in a cohesive manner can lead to a robust power plant and eventually proves the main point of the paper: “HREPP can be the future of power plants.”
- By having multiple systems working simultaneously, controlling output power and syncing the power demand and supply would be more accessible.
- These power plants can have a vast range of power production, even as extensive as the hydropower plants.
- This type of HREPP has a more extensive range of power production than other types of renewable energy power plants, but it can also replace all other power plants with the right design.

The governing principles and the methods of calculating the power production of each subsystem were introduced, and two hypothetical SCPAUPP were numerically studied for the average hottest day of the year, utilizing MATLAB coding to achieve the given data. The results indicate that replacing this type of HREPP with a proper design with a fossil-fueled power plant is possible. The study proposes that replacing HREPPs with fossil fuel-based power plants may be viable; however, given the complexities of transitions in the energy sector, caution is advised. Additional research and thorough examination are required to validate this transition's feasibility and long-term viability. HREPPs can replace or modify existing power plants (renewable energies or fossil-fueled). For example, the possibility of combining the SCPAUPP with the floating chimney and the water desalination system can be explored.

This study aimed to introduce the idea of HREPP, and by introducing an example (SCPAUPP), that illustrates these types of power plants can be those of the future and by observing the achieved data, we can be very optimistic about further investigating these types of HREPP as potential sources of power production in the future.

Nomenclature

$\dot{m}$	Mass flow rate, *kg/s*.
θ	Axis coordinate.
ρ	Density, *kg/m*^{3}.
A	Area, *m*^{2}.
I_r	Solar irradiation, *W/m*^{2}.
P	Pressure Pa.
$Q_{HE(t)}$	Heat flux of the spiral heat exchanger over the total area of the heat exchanger at any point in time, *W*.
T	Temperature, K.
$T_{f(l,t)}$	The outlet temperature of the heat exchanging fluid at length l and time t.
$T_{i(t)}$	The inlet temperature of the heat-exchanging fluid at time t, *K*.
c_p	Specific heat capacity, *J/kgK*.
h_C	Convective heat transfer coefficient, *W/m*^{2}*K*.
h_{Cond}	Conduction heat transfer coefficient, *W/m*^{2}*K*.
h_R	Radiative heat transfer coefficient, *W/m*^{2}*K*.
h_m	Mean heat-transfer coefficient between $T_{HE,i}$ and $T_{HE,o}$.
l_1	Depth of the upper convective zone, m.
l_2	Depth of the non-convective zone, m.
l_3	Depth of the lower convective zone, m.

Subscripts

a	Ambient air
ap	Air pumps
b	the blackened surface at the LCZ.
f	Fluid flow in the heat-exchanging medium.
F	Air Flow under the collector's roof.
g	Ground (base).
i	Inlet
liq	Liquid
o	Outlet
r	Collectors roof
sc	Solar chimney
w	Water

Acronyms

HPS	High-pressure storages
HREPP	Hybrid renewable energy power plant
LCZ	Lower convective zone.
LPS	Low-pressure storage.
MPS	Medium pressure storage.
NCZ	Non-convective zone.
RFA	The ratio of flow area.
SCPAUPP	Solar chimney pond alongside air pumps and Underwater compressed air storage power plant.
SCPP	Solar chimney power plant.
UCZ	Upper convective zone.
UWCAES	Underwater compressed air energy storage.

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