COMPARATIVE ANALYSIS OF SOLAR VACUUM CONICAL AND SPIRAL CAVITY RECEIVERS: DRIVING SUSTAINABLE ENERGY GOVERNANCE

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Abstract: *This study investigates the performance of a solar dish concentrator system equipped with vacuum conical and spiral cavity receivers, utilizing thermal oil as the working fluid. It specifically evaluates and compares the efficiency of vacuum and non-vacuum conical cavity receivers. The analysis is grounded in energy, exergy and environmental (3E) evaluation frameworks. These theoretical approaches assess the system's thermodynamic efficiency (energy/exergy) and its environmental impact mitigation potential. The methodology involves a comparative analysis of vacuum and non-vacuum conical cavity receivers, as well as vacuum spiral receivers, to determine their effects on the solar dish collector's efficiency. Thermal oil serves as the working fluid, and performance metrics (energy/exergy efficiency, overall system efficiency) are evaluated under real world conditions (e.g., seasonal variations, such as June and November 2021). The vacuum conical cavity receiver demonstrated superior performance, achieving energy and exergy efficiencies of approximately 73.45% and 17%, respectively, in June 2021. The highest improvements in energy (2.05%), exergy (2.17%), and overall efficiency (2.09%) were observed in November 2021 with the application of vacuum conical cavity receiver were compared to the non-vacuum one. The study underscores the role of vacuum receivers in enhancing solar system performance and provides policy recommendations to advance energy governance and sustainable energy practices through innovative solar technologies. These findings contribute to optimizing solar-efficient systems for sustainable development.*

Key words*: Vacuum cavity receiver; Comparison Study; Spiral and Conical cavity receivers; Energy governance; Sustainability; Policy recommendations.*

1. Introduction

Escalating worldwide power needs, alongside the critical demand for environmental stewardship, have propelled Renewable Energy Sources (RES) into the center of contemporary power discourse [1-3]. Traditional electricity production methods, mainly reliant on non-renewable resources, are now widely recognized for their detrimental ecological impacts, such as emissions linked to global warming,

atmospheric pollution, and participation in planetary climatic shifts [4, 5]. Such advancements can not only drastically cut humanity's carbon footprint [6] but also offer pathways toward supply independence, grid reliability, and financial progress across diverse socio-economic contexts. To address these concerns, countries internationally are implementing green alternatives—including solar, wind, hydro, and bioenergy systems as vital components within greener power infrastructures [7, 8]. Such advancements can not only drastically cut humanity's carbon footprint but also offer pathways toward supply independence, grid reliability, and financial progress across diverse socio-economic contexts.

As mentioned, SE stands as a pivotal resource in the quest for sustainable and clean energy solutions, harnessing the abundant radiation emitted by the sun [9, 10]. Among the various technologies employed to capture and utilize this energy, Solar Dish Concentrators (SDCs) have emerged as highly effective systems [10]. These concentrators utilize a parabolic reflector to focus sunlight onto a receiver, where the concentrated Solar Energy (SE) is converted into thermal energy [11, 12]. cavity receivers (CRs), designed with an enclosed structure, enhance the absorption of Solar Radiation (SR) while minimizing thermal losses due to their geometric configuration [13]. These receivers can take various forms, such as cylindrical or conical shapes, each specifically engineered to optimize thermal efficiency [14]. The development of CRs in SDCs has gained significant attention, focusing on innovations in materials, design, and thermal management to maximize performance [15]. As research advances, these CRs are increasingly recognized for their potential to support a range of applications, including electricity generation, industrial heating, and residential hot water production, thereby contributing effectively to the global transition toward RE sources.

Research is actively being conducted on the development of solar dish collectors equipped with CRs. Loni et al. [11, 13, 16] conducted a numerical optimization study on the performance of various shapes of CRs, including cubical, cylindrical, and hemispherical designs. Loni et al. [15, 17] then experimentally validated their analyses by constructing and testing these optimized CRs, utilizing pure thermal oil as the WF. Subsequently, Loni et al. [17-19] explored the effects of different nanofluids—specifically Al_2O_3/oil, CuO/oil, and SiO_2/oil—as the working fluid (WF) in SDCs with CRs, based on both numerical simulations and experimental findings. They found that the efficiency of the solar system (SS) can be improved using nanofluids.

Vacuum CRs represent a significant advancement in solar collector technology, particularly in concentrated solar power systems [20]. These receivers utilize a vacuum-insulated structure to greatly enhance thermal efficiency by minimizing heat loss through conduction and convection [21]. The design typically features a high-surface-area absorber that maximizes the capture of concentrated SR while reducing reflection losses, which leads to improved overall performance [22]. Additionally, the vacuum environment protects against environmental factors such as humidity and corrosion, thus contributing to greater durability and longevity. Vacuum CRs are versatile in their ability to operate with various WFs, including oils and molten salts, making them suitable for a wide range of applications, from electricity generation to thermal energy storage. Ongoing research efforts aim to optimize their design and materials further, underscoring their potential as the next generation of solar receivers in the RE landscape.

As mentioned in the literature review developing RE including SSs can be investigated as an interesting subject for research. This study aims to advance renewable energy (RE) systems, with a focus on solar technologies, by addressing critical inefficiencies in solar thermal receivers through innovative

design and governance-oriented analysis. The primary objective is to develop and evaluate a novel SDC system equipped with vacuum-insulated CRs—featuring distinct conical and spiral geometries—to mitigate convective and conductive heat losses, thereby significantly enhancing thermal efficiency. The research seeks to rigorously compare the performance of vacuum conical receivers against both non-vacuum conical counterparts and vacuum spiral receivers, employing integrated energy, exergy, and environmental (3E) assessments to quantify efficiency gains, sustainability benefits, and heat-loss reduction mechanisms. Furthermore, it explores how these technical advancements can inform energy governance frameworks to accelerate the adoption of resilient, inclusive renewable energy systems aligned with global sustainable development goals. The novelty of this work lies in its pioneering integration of vacuum insulation within uniquely shaped conical and spiral CRs for SDCs, a transformative approach to minimizing energy dissipation in solar thermal systems. By replacing conventional non-vacuum designs with vacuum-sealed receivers, the study directly targets a persistent challenge in solar technology: heat loss at the receiver stage. This innovation is further distinguished by its comparative analysis of two geometrically distinct vacuum receivers, offering new insights into how shape influences thermal retention and system efficiency under operational conditions. The integration of 3E metrics bridges technical performance evaluation with environmental and policy considerations, positioning the study as a holistic contribution to both engineering innovation and energy transition governance. By demonstrating measurable efficiency improvements—such as a 2.09% boost in overall system efficiency the research underscores the potential of vacuum receiver technology to redefine SE systems, not only as a technical upgrade but as a catalyst for reimagining energy governance paradigms to prioritize sustainability, equity, and security in the renewable energy transition.

2. Material and Methods

2.1. Energy, Exergy, and Environmental Analyses

This study uses computer models, experiments, and a method to compare different factors to assess how well SDCs work. These concentrators have special receivers shaped like vacuum cones and spirals. Thermal oil was used as the fluid, flowing at a rate of 300 ml per second, with a starting temperature of 100°C. The research used a method that looks at energy, exergy, and the environment together to fully understand how efficient a system is, how well it performs in terms of heat and energy, and its overall sustainability.

This study looks at a solar dish that has a vacuum spiral and a cone-shaped receiver. Figure 1 shows the current setup with a spiral cavity absorber. Figure 2 gives close-up views of the cavities: 2a shows the spiral shape, and 2b and 2c show the cone shape, which hasn’t been tested yet. The cone shape is shown in 3-D in Figure 2b and is explained in a side view in Figure 2c. Figure 3c shows its outer casing.

Figure 1. The investigated SS.

(a) **(b)**

Figure 2. The investigated CRs, a) spiral, and b) conical.

Both designs have an opening of 404 mm. The spiral design has 13 loops, while the conical receiver has 11 loops. The tubes in both designs are the same size, with an inside diameter of 10.5 mm and an outside diameter of 12.2 The area of the concentrator's opening is 10.29 square meters If we think of it as a flat surface, it has a concentration ratio of about 80.2 The distance to the focus point is 2.26 meters, and the angle of the edge is 45.6 degrees. This light design is a big plus. Table 1 lists the important design details. It shows that the concentrator reflects 92% of light, the receiver absorbs 95% of light, and the receiver emits 8% of the heat. These numbers are common for high-efficiency commercial systems, not for earlier experimental setups.

Table 1. Parameters of the analyzed configurations.

Parameter	Value
Concentration Ratio	80.2
The outer diameter of the concentrator	3.8 m
Inner diameter of the concentrator	0.4 m
Rim angle of the paraboloid	45.6°
Focal length	2.26 m
Aperture of the collector	10.29 m^2
Outer diameter of the spiral tube	12.2 mm

Inner diameter of the spiral tube	10.5 mm
Total coils in the spiral	13
Total coils in the conical	11
Diameter of the aperture (for both desings)	404 mm
Emittance of the absorber	0.08
Absorbance of the absorber	0.95
Reflectance of the concentrator	0.92

Energy analysis focused on quantifying heat gain, thermal losses, and overall Energy Efficiency (EE) using a steady-state energy balance model. SR data for The case study in 2021, sourced from NASA, served as the primary input. Key parameters, including cavity aperture area, absorber emissivity, and concentrator reflectance, were incorporated into equations governing radiation, convection, and conduction losses. For instance, radiation losses were calculated using the Stefan-Boltzmann law, while internal and external convection losses were modeled using Nusselt number correlations and thermal resistance principles. Thermal efficiency (η_{th}) was derived as the ratio of useful heat (Q_u) to incident SE (Q_{sol}).

Modeling thermal equilibrium at the collector component forms a crucial aspect of system simulation, particularly for technologies utilizing solar energy, such as thermal collectors. This concept involves quantifying the distinct power inputs to and outputs from the absorber unit to optimize overall performance. Incident solar radiation, concentrated onto its surface, constitutes the primary thermal source. Quantifying this input requires measuring irradiance levels while accounting for reflectance losses and concentrator optical efficiency. Furthermore, a circulating heat transfer fluid (HTF) traverses the unit, facilitating thermal absorption. The enthalpy gained by the HTF originates not only from the absorber surface's heat but also from ambient thermal contributions affecting the medium.

On the output side, energy losses can occur through several mechanisms. Convection plays a significant role, as heat transfer to the surrounding air is influenced by temperature differences, surface area, and environmental factors like wind velocity. Conduction can lead to heat loss through the material of the receiver itself, as heat escapes to the support structures or surrounding environment. Furthermore, thermal radiation emitted by the receiver surface can contribute to energy losses, becoming increasingly significant as the temperature of the receiver rises. In this way, we can find out how much useful heat is made by looking at the energy balance on the receiver. The SE we take in (Q_{abs}) splits into useful heat (Q_u) and wasted heat (Q_{loss}).

$$Q_{abs} = Q_u + Q_{loss} \tag{1}$$

When things are stable, heat loss can be grouped into three types: heat lost through radiation (Q_{rad}), heat lost inside through air movement ($Q_{conv,in}$), and heat lost outside through air movement ($Q_{conv,ex}$). You can figure out the heat losses (Q_{loss}) using these sentences:

$$Q_{loss} = Q_{rad} + Q_{conv,in} + Q_{conv,ex} \tag{2}$$

In this equation, Q_{rad} represents heat lost through radiation, $Q_{conv,in}$ refers to heat lost through internal convection, and $Q_{conv,ex}$ stands for heat lost through external convection. The total heat lost from the receiver is calculated like this:

$$Q_{rad} = \varepsilon \cdot \sigma \cdot A_{aper} \cdot (T_r^4 - T_{am}^4) \tag{3}$$

In this equation, ε is a measure of how well a surface emits heat, σ (W-m^{-2}-K^{-4}) is a constant known as the Stefan-Boltzmann constant, which is about 5.67×10^{-8}, A_{aper} (m²) is the area of the opening

in the cavity, T_r (K) is the temperature of the surface inside the cavity, and T_{am} (K) is the temperature of the surrounding environment. The heat lost inside due to convection can be shown using these equations [23]. In this model, we use the Nusselt number for the inside space (Nu_{in}) and the heat transfer rate inside (h_{in}).

$$Q_{conv,in} = A_{cav} \cdot h_{in} \cdot (T_r - T_{am}) \tag{4}$$

$$h_{in} = Nu_{in} \frac{k_{air}}{D_{aper}} \tag{5}$$

$$Nu_{in} = 1.635 \cdot Re^{0.38} Pr^{-1.2} \left(\frac{D_{aper}}{D_{cav}}\right)^{0.892} [1 + cos(\theta)]^{0.285} \tag{6}$$

The external convection thermal losses ($Q_{conv,ex}$) refer to the heat that escapes from the outside surface of the CR to the surrounding air. In this study, these losses include the heat loss that happens inside the cavity. To figure out these heat losses, we use something called the thermal resistance of the space (R_{cav}), as shown in the equations below.

$$Q_{conv,ex} = \frac{T_r - T_{am}}{R_{cav}} \tag{7}$$

In this equation, T_r (K) is the temperature of the receiver's surface, T_{am} (K) is the surrounding temperature, and R_{cav} can be figured out like this:

$$R_{cav} = R_{conv,ex} + R_{cond} \tag{8}$$

Where

$$R_{conv,ex} = \frac{1}{h_{out} \cdot A_{cav}} \tag{9}$$

$$h_{out} = Nu_{out} \frac{k_{air}}{D_{cav}} \tag{10}$$

On the other side, R_{cond} can be figured out using this equation:

$$R_{cond} = \frac{t_{ins}}{k_{ins} \cdot A_{cav}} \tag{11}$$

The insulation is 2 cm thick and made of mineral wool, which has a thermal conductivity of 0.062 W-m-K. EE ca be figured out like this:

$$\eta_{th} = \frac{Q_u}{Q_{sol}} \tag{12}$$

On the other side, Exergy analysis extended the evaluation to assess the system's ability to convert SE into usable work. The Petela model was applied to compute the exergy of solar irradiation (E_s), accounting for the reference (T_0=298 K) and solar source temperatures (T_{sun}=5770 K). Useful exergy (E_u) incorporated temperature gradients, pressure drops, and pumping work, with friction factors and pressure losses calculated using empirical correlations. Exergy efficiency (η_{ex}) was defined as the ratio of E_u to E_s. Pumping work demand (W_p) was adjusted using an assumed electrical efficiency of 33%, reflecting real-world energy conversion limitations. As a performance metric, exergy efficiency gauges a solar thermal device's function, comparable to a heat engine. It quantifies the combined performance when such a collector operates alongside an ideal heat engine to generate work. For the collector itself, exergy efficiency (η_{ex}) is defined as usable output (E_u) divided by received solar input (E_s). This relationship can be shown using math as:

$$\eta_{ex} = \frac{E_u}{E_s} \tag{13}$$

The useful exergy output of the solar collector (E_u) is expressed using this equation [16]:

$$E_u = m \cdot c_p \left(T_{out} - T_{in} - T_0 \, ln\left(\frac{T_{out}}{T_{in}}\right)\right) - \frac{T_0}{T_{fm}} \frac{m \cdot \Delta P}{\rho_{fm}} \tag{14}$$

Here, the mean fluid temperature represents the average between the inlet and outlet flow values. Furthermore, incident solar radiation exergy (E_s) is quantified via the Petela model [16], an established method suitable for analyzing direct beam radiation, such as that utilized by solar dish collectors.

$$E_s = Q_s \cdot \left(1 - \frac{4}{3} \cdot \frac{T_0}{T_{sun}} + \frac{1}{3} \cdot \left[\frac{T_0}{T_{sun}}\right]^4\right) \quad (15)$$

The reference temperature (T_0) and the sun temperature (T_{sun}) were assumed at 298 K, and 5770 K, respectively [16].

It should be mentioned that the friction factor (f_r) can be calculated using the provided equation, which is essential for understanding flow resistance in the system and plays a crucial role in fluid dynamics. The pressure drop (ΔP) is computed using a formula that determines the pressure loss due to friction within the system, considering the friction factor, pipe length, diameter, fluid density (ρ), and flow velocity (u). The pumping work demand (W_p) illustrates the amount of work required from the pump to overcome the calculated pressure drop, which depends on the mass flow rate (m) and fluid density. The solar collector is designed to generate useful heat while also consuming energy for circulation; this dual requirement makes it necessary to evaluate the overall system efficiency comprehensively. The Overall Efficiency (OE) (η_{ovr}) expression combines the useful heat produced by the collector, the pumping work adjusted for electrical efficiency, and the total available SE, providing a complete measure of energy performance. In this context, a standard electrical efficiency value of around 33% has been selected, a common assumption that can significantly affect overall calculations. The friction factor (f_r) can be determined using the following equation [24]:

$$f_r = [0.79 \cdot ln(Re) - 1.64]^{-2} \quad (16)$$

The pressure drop (ΔP) across a system is calculated using the formula:

$$\Delta P = f_r \cdot \frac{L}{D} \cdot \left(\frac{1}{2} \cdot \rho \cdot u^2\right) \quad (17)$$

The demand for pumping work (W_p) is calculated as follows:

$$\Delta W_p = \frac{m \cdot \Delta P}{\rho} \quad (18)$$

While the OE is:

$$\eta_{ovr} = \frac{Q_u - \frac{W_p}{\eta_{el}}}{Q_s} \quad (19)$$

In this analysis, the electrical efficiency is typically around 33%, and this value has been utilized in the calculations presented in this work. On the other hand, related to the environmental analyses, the annual amount of CO_2 emissions reduced is [25]:

$$\varphi_{CO_2} = \frac{\psi_{CO_2} \times E_{en,ann}}{10^3} \quad (20)$$

Additionally, carbon credit denoted as Z_{CO_2}, is [25]:

$$Z_{CO_2} = z_{CO_2} \times \varphi_{CO_2} \quad (21)$$

Comparative analyses between vacuum/non-vacuum conical receivers and vacuum conical/spiral receivers were structured around seasonal variations. Performance metrics, including efficiency improvements and environmental parameters, were tabulated monthly to identify trends. The study emphasized the role of vacuum insulation in minimizing convective and conductive losses, with design variations (spiral vs. conical) analyzed for their impact on heat retention and fluid dynamics. Assumptions, such as insulation properties (mineral wool, *kins* =0.062 W-m-K) and operational hours (2500 annually), were consistent with commercial SSs. This comprehensive approach bridged technical innovation with policy relevance, providing actionable insights for advancing solar technology and sustainable energy governance frameworks. The radiation data were used based on data reported by NASA (https://www.nasa.gov/) in 2021 for Tehran, Iran as the case study (Figure 3). It should be mentioned that all of the used data are based on reported monthly data.

It is important to note that all Equations in modeling section inherently provide an instantaneous radiative flux. Given that our input climate data are obtained as monthly mean values from the NASA database, the resulting calculated via Equations represents the mean monthly radiative loss under a quasi-steady-state assumption. We acknowledge that a rigorous time-integration over hourly/daily temperature fluctuations is not within the scope of this work due to data availability, and this approximation is considered acceptable for the comparative parametric analysis presented here.

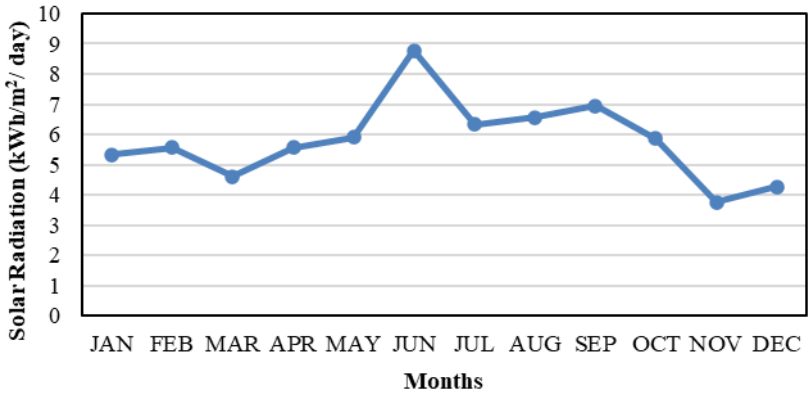

Figure 3. Variation of SR in The case study, 2021 in Tehran, Iran as the case study.

2.2. Validation

The spiral case model was checked against the experimental results mentioned in Reference [16]. Figure 4 shows a comparison between the model that developed and the reported results from experiments. Changes were made to make sure the model matched the test conditions, including the starting temperature, flow rate, and sunlight intensity shown in Figure 4. The average difference in thermal efficiency was 5.15%, and the average difference in outlet temperature was 4. 05%, as shown in Figure 4. These differences are quite small, which shows that the model we created is trustworthy.

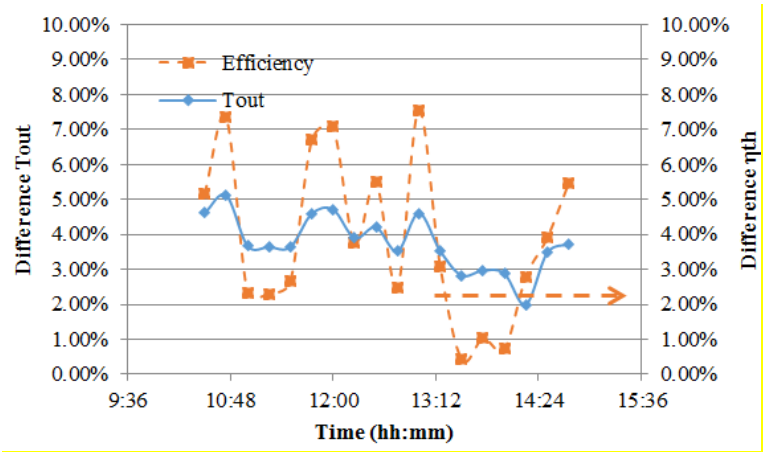

Figure 4. Validation data from the reported data in Ref. [16] and numerical results in the current study.

2.3. Energy Governance and Sustainable Development

Energy governance significantly influences the trajectory of sustainable development, especially when it comes to the advancement and implementation of solar energy systems. This governance framework is crucial as countries worldwide seek to adapt to sustainable energy alternatives amidst escalating environmental concerns and energy demands. Effective energy governance ensures that the deployment of solar technologies not only aligns with environmental, economic, and social objectives but also maximizes their potential for positive impact.

The integration of solar energy into national energy policies requires a comprehensive, multi-faceted approach. This involves the establishment of robust regulatory frameworks that govern how solar technologies are developed, deployed, and maintained. Well-defined policies can streamline the permitting process for solar projects, reduce bureaucratic hurdles, and provide clarity for investors. Policymakers need to consider various aspects of energy governance, such as zoning laws, safety regulations, and interconnection standards, which play pivotal roles in facilitating the growth of solar infrastructure.

Financial incentives are a cornerstone of effective energy governance in promoting solar energy adoption. Governments can implement a range of financial mechanisms to make solar technologies attractive and attainable. Subsidies can lower the initial capital costs associated with purchasing and installing solar systems, while tax breaks can encourage both businesses and households to invest in renewable energy. Feed-in tariffs guarantee a fixed payment for energy generated from solar sources, providing a reliable revenue stream that can help finance solar projects. By implementing these incentives, governments not only stimulate the growth of the solar industry but also stimulate local economies, creating jobs and generating new investment opportunities.

As governments push for the widespread adoption of solar energy, it's essential to consider the broader social implications of these policies. Sustainable development in the context of solar systems must prioritize social equity to guarantee that marginalized and underserved communities are not left behind in the transition to renewable energy. Many low-income households and rural areas struggle with consistent access to electricity, a challenge that renewable energy can help address. Targeted programs that focus on improving energy affordability and accessibility can serve to bridge the energy divide, empowering these communities. This may include initiatives such as community solar projects, which allow local residents to collectively invest in solar power or benefit from shared solar installations.

Furthermore, energy governance must ensure that these initiatives are designed with input from the communities they serve, promoting engagement and awareness. By involving local stakeholders in the planning and implementation of solar projects, programs can be tailored to the specific needs and preferences of communities, fostering a sense of ownership and commitment to sustainability efforts. Effective outreach and education programs can also enhance understanding of solar energy’s benefits and impact, enabling communities to embrace these technologies enthusiastically.

Generally, the interplay between energy governance and sustainable development in the context of solar energy is complex yet essential. By establishing clear policies, financial incentives, and inclusive practices, nations can create an environment conducive to the growth of solar technologies. As such, these strategies not only help to mitigate the impacts of climate change but also promote social equity and economic empowerment, ultimately contributing to a more sustainable and equitable energy future for all. The success of solar energy adoption hinges on this effective governance, which ensures that the

benefits of renewable energy are widely shared and that the transition to a sustainable energy landscape is both just and inclusive.

3. Results and Discussion

3.1. Conical Vacuum Cavity

In this part, the energy analysis results of the solar dish concentrator (SDC) with the vacuum conical cavity receiver (CR) are reported. Thermal oil served as the working fluid (WF) with a volume flow rate of 300 ml/s and an inlet temperature of 100 °C, and system performance was evaluated under varying solar radiation (SR) in the case study throughout 2021. Figures 5a and 5b show that cavity heat gain (CHG) and energy efficiency (EE) closely followed SR fluctuations, both peaking in June 2021 at approximately 8500 W and 73.45 %, respectively. The similar trends in EE and CHG stem from their interdependent relationship: higher SR directly increases CHG, and because the vacuum conical CR minimizes convective and conductive losses through its vacuum insulation, a larger proportion of absorbed heat is converted into usable thermal energy. The conical geometry, high-absorptivity coating (95 %), and low-emissivity surface (0.08) further enhance heat capture and retention. During peak SR periods, the system operates near its thermodynamic optimum, aligning heat absorption with fluid heat capacity to reduce entropy generation. Thus, the vacuum conical CR's efficient harnessing of SR combined with its loss-suppressing design creates a positive feedback loop where increased CHG directly elevates EE, underscoring the critical role of receiver geometry in optimizing solar thermal system performance.

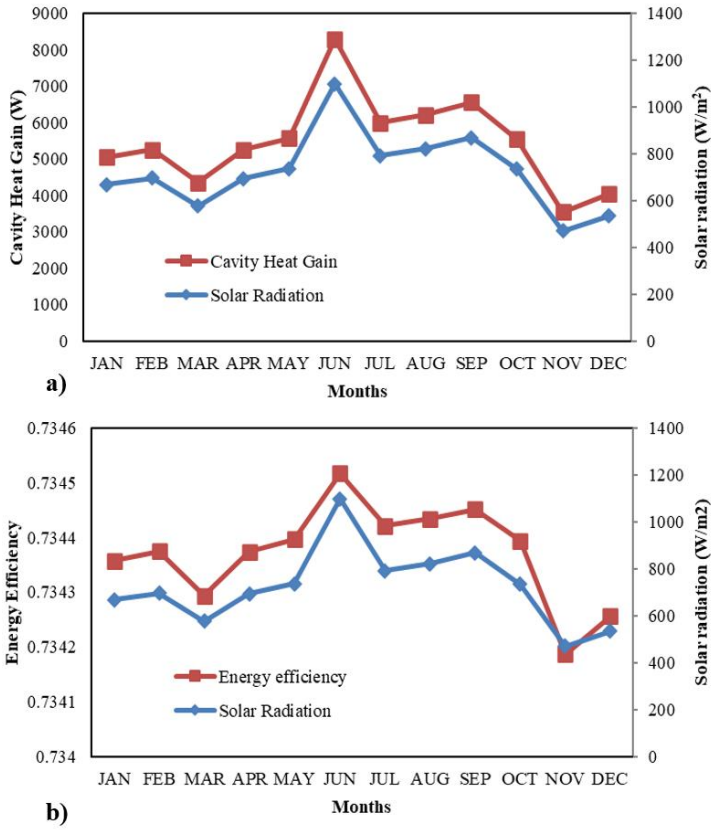

Figure 5. Variation of a) CHG, and b) EE of the SS with the vacuum conical CR under variation of SR throughout 2021 in the case study.

This section presents the exergy analysis results for the solar dish concentrator (SDC) with a conical vacuum cavity receiver, using thermal oil (300 ml/s, 100°C inlet temperature) under varying solar radiation (SR) levels in the 2021 case study. Figures 6a and 6b show that exergy gain closely followed SR fluctuations, peaking at about 1800 W in June 2021. Exergy efficiency similarly reached approximately 17% in the same month. The similar trends between exergy efficiency and exergy gain stem from their thermodynamic relationship: exergy gain represents the useful work potential from energy input, and exergy efficiency measures how effectively that potential is harnessed. When exergy gain rises due to favorable conditions (e.g., higher SR), both metrics improve, provided losses do not increase proportionally. External factors like temperature, pressure, and energy source quality affect both. The vacuum receiver enhances this correlation by suppressing convective and conductive losses, preserving the temperature potential of absorbed solar energy and minimizing entropy generation. Higher SR raises the receiver surface temperature, increasing the Carnot factor and exergy gain. The receiver's low-emissivity surface (0.08) curtails radiative losses, and its geometry ensures uniform heat transfer, reducing exergy destruction. During peak irradiation, the system operates near its ideal thermodynamic state, increasing the exergy content of incoming radiation (Petela model) while optimized fluid flow maximizes the exergy output ratio. The conical design also reduces flow resistance and pumping work, and its high-absorptivity coating (95%) minimizes reflection losses. In summary, the vacuum conical receiver's ability to retain high-temperature heat with minimal losses, combined with hydrodynamic and geometric optimizations, directly elevates exergy gain (e.g., 1800 W in June) and exergy efficiency (17%), highlighting the importance of suppressing irreversibilities to harness solar energy's work potential.

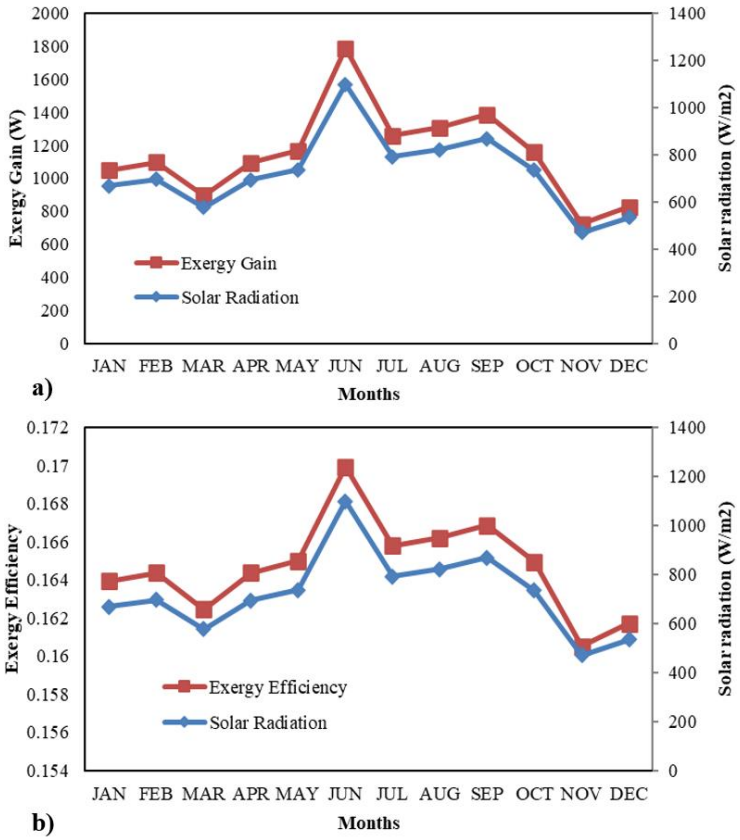

Figure 6. Variation of a) Exergy gain, and b) Exergy efficiency of the SS with the vacuum conical CR under variation of SR throughout 2021 in the case study.

This section outlines the findings from the equivalent thermal output and OE analyses conducted on the SDC that is outfitted with a conical vacuum CR. Thermal oil served as the solar WF, operating at a VFR of 300 ml/s and an IT of 100°C. The performance of the SS incorporating the vacuum conical CR was evaluated about the fluctuations in SR levels throughout 2021 in The case study.

Figures 7a and 7b illustrate the changes in equivalent thermal output, and OE of the SS utilizing a vacuum conical CR, responding to variations in SR throughout 2021 in The case study. Figure 7a reveals that equivalent thermal output closely followed the fluctuations in SR over the year, reaching a peak of approximately 8500 W in June 2021. Similarly, Figure 7b indicates that the variations in OE exhibited a comparable trend to the SR and CHG throughout 2021, with a maximum efficiency of around 72.9% recorded in June 2021.

The similar trends observed in equivalent thermal output and OE alongside variations in CHG and SR can be attributed to their interrelated nature within the system. Equivalent thermal output represents the amount of usable thermal energy produced by the system, while OE reflects how effectively the system converts input energy (in this case, SR) into that usable thermal output. As SR levels fluctuate, they directly influence the CHG; higher radiation results in increased heat absorption by the CR. This increased CHG leads to a corresponding rise in equivalent thermal output since more thermal energy is being generated for use. Consequently, as the thermal output increases due to greater heat absorption, the OE of the system also improves, provided that losses are not disproportionately higher.

Moreover, both equivalent thermal output and OE are impacted by the same factors, such as the design of the CR, the properties of the WF, and environmental conditions. When the system operates under optimal conditions with high SR, the enhancements in CHG yield a direct increase in thermal output and efficiency. This interconnectedness results in the observed similar trends, where increased SR enhances both CHG and the overall performance of the system.

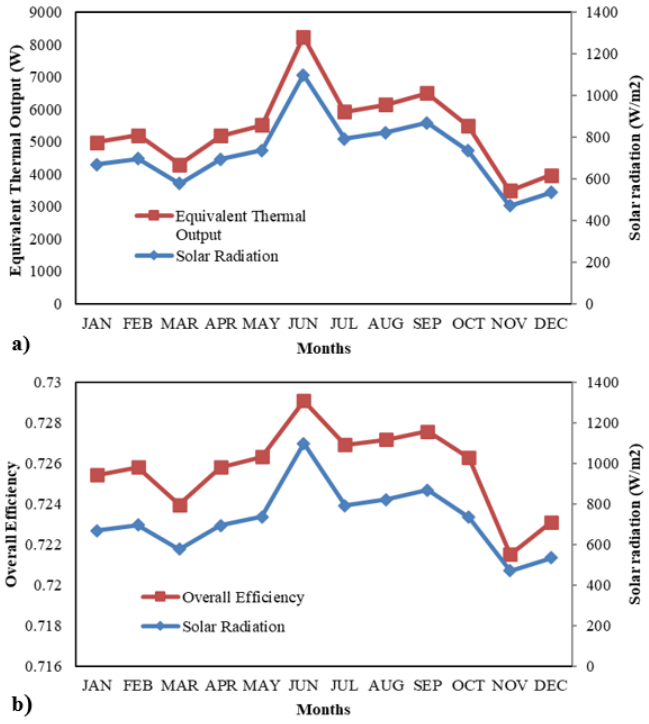

Figure 7. Variation of a) Equivalent Thermal Output, and b) OE of the SS with the vacuum conical CR under variation of SR throughout 2021 in the case study.

3.2. Improving Vacuum Conical Cavity

Table 2 presents the enhancements in energy, exergy, and OE of the SS utilizing a vacuum conical CR compared to the non-vacuum in 2021 in the case study. The data indicates that the most significant improvements in energy, exergy, and OE were recorded at 2.05%, 2.17%, and 2.09%, respectively, in November 2021. This is due to the design of the vacuum conical CR is likely to contribute to its greater efficiency compared to a non-vacuum. The vacuum layer reduces convective and conductive heat losses, which means that more of the collected SE is converted into useful energy, thus improving exergy and OE.

Table 2. Improvement of energy, exergy, and OE.

	Efficiency Improvement (%)		
Month	Energy	Exergy	Overall
JAN	1.64	1.74	1.66
FEB	1.60	1.70	1.62
MAR	1.79	1.90	1.82
APR	1.60	1.70	1.62
MAY	1.54	1.65	1.56
JUN	1.25	1.36	1.26
JUL	1.48	1.58	1.50
AUG	1.45	1.56	1.47
SEP	1.41	1.51	1.43
OCT	1.55	1.65	1.57
NOV	2.05	2.17	2.09
DEC	1.89	2.00	1.91

This section presents the findings concerning the variation of environmental parameters in the SS using a vacuum conical CR compared to the non-vacuum one. Thermal oil was chosen as the solar WF, operating at a VFR of 300 ml/s and an IT of 100°C. The performance improvements of the SSs featuring both vacuum conical CRs compared to the non-vacuum ones were evaluated regarding fluctuating SR levels throughout 2021 in the case study.

Table 3 illustrates the variations in environmental parameters, including annual CO_2 emissions and carbon credits of the SSs employing vacuum and non-vacuum conical CRs during 2021 in The case study. The data indicates that the annual CO_2 emissions for the systems with the vacuum and non-vacuum conical CRs peaked in June 2021, with recorded values of 42.31 tons and 41.78 tons, respectively. This peak in emissions can likely be attributed to a combination of factors, including higher SR levels during that month, which would increase energy production and the associated emissions if the systems were not optimized for efficiency.

Furthermore, the carbon credits for the systems using vacuum and non-vacuum conical CRs also reached their highest values of 613.42 ($), and 605.82 ($), respectively. The slightly higher carbon credits associated with the vacuum system may indicate its superior efficiency in converting SE into usable energy, thereby reducing emissions and enhancing its environmental performance. The distinction in both CO_2 emissions and carbon credits between the two types of receivers underscores the impact of design and efficiency on the overall environmental footprint of SE systems.

Table 3. Variation of environmental parameters of the SS using vacuum conical CR compared to the non-vacuum one during 2021 in the case study.

	Conical CR			
	Vacuum		Non-Vacuum	
Month	Ph (tonco2)	Zeth ($)	Ph (tonco2)	Zeth ($)
JAN	25.72	373.00	25.31	366.99
FEB	26.83	389.08	26.41	382.96
MAR	22.21	321.98	21.81	316.31
APR	26.78	388.38	26.36	382.27
MAY	28.42	412.14	27.99	405.87
JUN	42.31	613.42	41.78	605.82
JUL	30.54	442.89	30.10	436.42
AUG	31.65	458.97	31.20	452.39
SEP	33.44	484.83	32.97	478.08
OCT	28.28	410.04	27.85	403.79
NOV	18.11	262.58	17.74	257.30
DEC	20.57	298.22	20.19	292.70
Yearly	334.86	4855.54	329.72	4780.90

3.3. Comparison between Conical and Spiral Vacuum Cavities

This section compares the performance of a solar dish system using a vacuum conical cavity receiver versus a vacuum spiral cavity receiver, with thermal oil as the working fluid at 300 ml/s and 100°C inlet temperature, under varying solar radiation in a 2021 case study. As shown in Table 4, the vacuum spiral receiver yielded the most significant gains over the conical design in November 2021: energy efficiency rose by 7.13%, exergy efficiency by 4.42%, and overall efficiency by 4.77%. While both receivers benefit from vacuum insulation that reduces thermal losses, the spiral cavity appears to offer additional design advantages—such as superior heat transfer dynamics and operational characteristics—that further minimize dissipation and optimize conversion of absorbed heat into usable energy. These combined factors explain the marked efficiency improvements observed in November.

Table 4. Improvement of energy, exergy, and OE of the SS using vacuum conical CR compared to the vacuum spiral CR during 2021 in the case study.

	Efficiency Improvement (%)		
Month	Energy	Exergy	Overall
JAN	4.26	2.38	2.57
FEB	3.98	2.18	2.36
MAR	5.34	3.15	3.40
APR	3.99	2.19	2.37
MAY	3.61	1.92	2.08
JUN	1.59	0.47	0.54
JUL	3.18	1.62	1.75
AUG	2.98	1.47	1.60

SEP	2.69	1.26	1.38
OCT	3.64	1.95	2.10
NOV	7.13	4.42	4.77
DEC	5.97	3.60	3.88

This section outlines the findings regarding the variation of environmental parameters of the SS using a vacuum conical CR compared to the vacuum spiral CR. Thermal oil was selected as the solar WF, operating at a VFR of 300 ml/s and an IT of 100°C. The performance improvements of the SS, incorporating both the vacuum conical and spiral CRs, were assessed about the variations in SR levels throughout 2021 in The case study.

Table 5 displays the variations in environmental parameters, including the annual CO2 emissions and carbon credits of the SS utilizing a vacuum conical CR compared to a vacuum spiral CR in 2021 in The case study. The data shows that the annual CO2 emissions for the SSs with the vacuum conical and vacuum spiral CRs were at their highest in June 2021, recording values of 42.31 tons and 42.98 tons, respectively. Additionally, it can be concluded that the carbon credit of the SS using vacuum conical and vacuum spiral CRs were the highest values at 613.42 ($), and 623.15 ($) in June 2021, respectively. It can be seen the SS with the vacuum spiral CR resulted in better environmental influence compared to the application of vacuum conical CR. The vacuum spiral CR may allow for more effective absorption of SR, translating into higher thermal efficiency. This increased efficiency can lead to lower CO2 emissions because more SE is converted into usable energy, reducing reliance on fossil fuels.

Table 5. Variation of environmental parameters of the SS using vacuum conical CR compared to the vacuum spiral CR during 2021 in the case study.

	Vacuum CR			
	Conical		Spiral	
Month	Ph ($tonco_2$)	Zeth ($)	Ph ($tonco_2$)	Zeth ($)
JAN	25.72	373.00	26.82	388.90
FEB	26.83	389.08	27.90	404.56
MAR	22.21	321.98	23.39	339.19
APR	26.78	388.38	27.85	403.88
MAY	28.42	412.14	29.45	427.03
JUN	42.31	613.42	42.98	623.15
JUL	30.54	442.89	31.52	456.99
AUG	31.65	458.97	32.60	472.66
SEP	33.44	484.83	34.33	497.85
OCT	28.28	410.04	29.31	424.99
NOV	18.11	262.58	19.40	281.30
DEC	20.57	298.22	21.80	316.03
Yearly	334.86	4855.54	347.35	5036.52

3.4. Sustainable Energy Future

The numerical results obtained from the 3E (energy, exergy, and environmental) analyses provide a concrete, data-driven foundation for assessing the sustainable energy future enabled by these advanced

vacuum receiver designs. The performance metrics are not merely academic figures; they translate directly into tangible environmental benefits and governance priorities.

Quantitatively, the vacuum conical receiver achieved a peak energy efficiency of 73.45% and an exergy efficiency of 17% in June 2021, corresponding to an equivalent thermal output of approximately 8,500 W (Figs. 5–7). When compared to its non-vacuum counterpart, the vacuum conical design yielded a maximum improvement of 2.05% in energy, 2.17% in exergy, and 2.09% in overall efficiency during November 2021 (Table 2). While these percentage increases may appear modest, their cumulative annual impact is substantial: the vacuum conical receiver enabled a greater annual CO_2 emission reduction (334.86 tons) compared to the non-vacuum design (329.72 tons), translating to an additional $74.64 in annual carbon credits (Table 3). Over a 20-year operational lifespan, this incremental improvement alone could mitigate an extra ~103 tons of CO_2, demonstrating that even marginal efficiency gains yield significant long-term climate benefits.

More strikingly, the comparative analysis between the two vacuum geometries revealed that the spiral cavity receiver substantially outperforms the conical design. The vacuum spiral receiver achieved improvements of 7.13% in energy, 4.42% in exergy, and 4.77% in overall efficiency over the conical receiver in November 2021 (Table 4). This superior performance translates directly into enhanced environmental stewardship: the vacuum spiral receiver reduced annual CO_2 emissions by 347.35 tons, compared to 334.86 tons for the conical vacuum design, resulting in a yearly carbon credit surplus of approximately $180.98 (Table 5).

These quantifiable results underscore a critical nexus between engineering innovation and energy governance. The data demonstrate that strategic investments in receiver geometry (spiral vs. conical) and vacuum insulation are not merely technical optimizations but high-yield policy levers. For policymakers, these numbers provide clear evidence to justify:

- Targeted R&D funding: Prioritizing spiral vacuum receivers offers a measurable 4.77% overall efficiency advantage, which can be translated into specific grid-decarbonization targets.
- Performance-based financial incentives: Subsidies and tax credits can be tiered based on receiver efficiency thresholds (e.g., systems exceeding 72% overall efficiency), using the vacuum conical/spiral results as benchmarks.
- Lifecycle carbon accounting: The verified CO_2 reduction potential (e.g., an extra 12.49 tons/year for the spiral over the conical) provides empirical data for national greenhouse gas inventory reporting and carbon trading frameworks.
- Furthermore, the exergy efficiency of 17%—though appearing low relative to energy efficiency—highlights the inherent thermodynamic irreversibilities in solar thermal conversion. This 17% figure serves as a critical baseline for setting realistic, science-based performance standards in national renewable energy mandates.

Ultimately, the numerical evidence from this study moves the sustainable energy discourse from abstract aspiration to accountable metrics. By quantifying exactly how much efficiency is gained (e.g., 2.05% to 7.13%) and exactly how much CO_2 is offset (e.g., 334.86 to 347.35 tons/year), this analysis equips energy governors, investors, and communities with the hard data needed to make informed decisions. The transition to a sustainable energy future, therefore, depends not only on deploying solar technologies but on rigorously evaluating their performance through the integrated 3E lens—ensuring that governance frameworks are continuously updated to reflect the best available empirical evidence.

3.5. Suggested Policies

To advance solar energy (SE) systems, including solar dish concentrators with vacuum cavity receivers, and to foster sustainable energy governance [26], the following policies are recommended:

- **Financial incentives**: Offer tax credits, grants, and subsidies to drive R&D, deployment, and investment in low-carbon solar technologies.
- **Streamlined regulations**: Simplify permitting and installation processes for SE systems, ensuring compatibility with existing energy infrastructure.
- **Local manufacturing and jobs**: Promote domestic production of SE components and support workforce training to create jobs in the renewable energy sector.
- **Community engagement**: Involve local communities through public consultations, workshops, and education campaigns to build support and awareness.
- **Equitable access**: Subsidize installations for low-income households and develop community solar projects to serve underserved populations.
- **Environmental assessments**: Mandate comprehensive impact evaluations for all SE projects to inform decision-making.
- **R&D funding**: Allocate government resources to improve the efficiency and integration of solar dish collectors and vacuum receivers.
- **Public-private partnerships**: Encourage collaboration with NGOs and the private sector for knowledge sharing, financing, and community-level deployment.
- **Renewable energy standards**: Establish targets for solar energy generation, explicitly including innovative technologies like solar dish concentrators.
- **Monitoring and evaluation**: Implement systems to assess performance, sustainability, and equity, enabling evidence-based policy adjustments.

Adopting these policies will support the development and integration of SE systems, promoting innovation, resilience, and equitable energy access for all communities.

4. Conclusion

This paper examines a SDC featuring vacuum conical and spiral CRs, utilizing thermal oil as the solar WF. The analysis focused on energy, exergy, and environmental (3E) evaluations of the SS. The performance of the system was compared between vacuum and non-vacuum conical CRs. Additionally, the impact of employing vacuum conical and vacuum spiral CRs on the performance of the solar dish collector was investigated. The study also explored how enhancing energy governance could be achieved through the development of the proposed SS, leading to several policy recommendations. The results showed that the SS using a vacuum conical CR revealed significant trends related to SR fluctuations throughout the year, with peak CHG and equivalent thermal output reaching approximately 8500 W in June 2021. EE peaked at 73.45%, while exergy gain also mirrored SR patterns, peaking at 1800 W and showing a maximum exergy efficiency of 17% in the same month. Comparatively, significant improvements in energy, exergy, and OE of 2.05%, 2.17%, and 2.09% were noted for the vacuum conical receiver relative to its non-vacuum counterpart in November 2021. CO2 emissions for both vacuum and non-vacuum systems peaked in June 2021, at 42.31 tons and 41.78 tons, respectively, with corresponding carbon credits reaching their highest values. Furthermore, the analysis indicated that vacuum spiral CRs outperformed vacuum conical receivers, achieving improvements in energy, exergy, and OE as 7.13%, 4.42%, and 4.77%, respectively. The findings highlight the need for sustainable

energy governance through the advancement of solar technologies and recommend policies such as tax incentives and grants to foster innovation and investment in low-carbon energy solutions.

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