INTRODUCTION

The negative influence of human beings on the planet mostly causes environmental decay. The increase in population and industrialization has largely impacted the natural surroundings, affecting the ecosystem and human health. This impact is originated by an elevated energy demand, which is mostly produced using traditional hydrocarbon-based power plants, burning a vast amount of natural and limited resources. Qatar is not the exception; gas power plants and diesel generators mainly power the country's rapid growth; however, the interest in researching and exploiting renewable sources of energy is growing exponentially. Nonetheless, the studies primarily focus on improving leading technologies such as photovoltaic (PV) panels, which still present difficulties in maintaining its efficiency during elevated temperatures despite all the advancements made. Correspondingly, PV or solar thermal, which is also a well-known form of harnessing the sun's potential, requires a large investment during its development, due to special materials and equipment, and throughout its

Comparison of the influence of solid and phase change materials as a thermal storage medium on the performance of a solar chimney

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Abstract
This paper studies the heat storage system's influence on a solar chimney's power production. This study considers several material types, including solid and phase change materials, at the bottom section of a solar chimney for energy storage, and evaluates their effects on the energy yield and capacity to prolong the power output during the absence of the sun. A computational fluid dynamic model using COMSOL Multiphysics is performed to carry out this work. An initial steady-state analysis using average monthly irradiance is implemented, after which the top two solid and phase change material options are selected. Subsequently, a time-dependent simulation using a typical summer day is carried out for the chosen storage materials. The overall performance results are comparatively assessed in terms of average temperature, power generation, and efficiency. As a result, bismuth-led-tin-cadmium and magnesium chloride hexahydrate present the highest power production among the phase change materials, giving a yearly average power output of 27.46 kW and a storage temperature of about 346 K. On the other hand, sandstone offers the highest overall annual average power production, yielding 31.49 kW, and a storage temperature of 352.17 K. This material also reflects the highest yearly average energy and exergy efficiencies with 0.122% and 0.128%, respectively.

KEYWORDS
computational fluid dynamics, heat storage, phase change, solar energy, wind
operational phase, originated mostly by the existence of circulation fluids or solar tracking elements.

Currently, a vast amount of studies regarding sustainable sources of energy are being carried out. One technology that addresses this topic is called solar chimney (SC), a structure capable of harnessing solar irradiation to produce electricity via a wind turbine located at the chimney entrance. To accomplish this objective, the SC must include a transparent collector to allow the solar radiation to access the structure, a chimney, from which the airflow will exit, an underground storage layer to absorb the heat, and the previously mentioned wind turbine. Despite not being well known, SC technology has been a source of a different range of studies. Mathematical models and computational fluid dynamics (CFD) are the most common approach; however, experimental studies of varying shapes and sizes have also been executed. The main point of comparison of an SC’s performance is a large prototype that existed in Spain during the 1970s. Hence, most results obtained by digital forms of modeling are proven to be reliable, based on their similarity with the Spanish model. From this perspective, significant findings have been made. For example, both CFD and mathematical analysis emphasize the impact of the pressure drop across the turbine on the energy output, yielding higher values once contrasted with the Spanish prototype. For example, the latter generated 35 kW at 750 W/m², while the digital approach produced 40 kW at 200 W/m². Continuing with the CFD prototype relation, one study built a small model and compared it with computer simulations, highlighting that a decrease in the inlet height increases the chimney’s wind speed. This approach also confirmed that the constructed model results concur with the simulations obtaining a maximum error of 4.7%.

Different ways to improve an SC’s efficiency have been examined, being the design and distribution of its elements a significant part of it. The most analyzed aspect is the collector’s shape; despite all of them having a circular aspect (looked from above), several approaches have been taken between the collector’s entrance and its connection to the chimney. Horizontal, sloped, and a combination of these two have been analyzed; even one novel design including partitioning walls under the collector was looked into, all of which indicate that the horizontal option is less effective than the rest. Furthermore, these studies also concur that energy production increases with the chimney’s height, while the collector’s diameter has a limited influence, meaning that this element will allow a higher production up to a specific limit based on the overall design of the SC. Regarding the design, another interesting finding was the inversely proportional relationship between the chimney’s radius and the wind speed, meaning that a reduction in the radius increases the velocity of the air.

To utilize the entire infrastructure of an SC and increase its efficiency by creating more than one output, freshwater has also been obtained using an integrated SC. Diverse designs have been made based on this principle; the most popular one is substituting the SC’s heat storage section for water basing. Other less common approaches such as seawater spaying stations or a supercharged ventilator in the exit of the chimney have also been implemented. All in all, this output diversification generates an increase in the efficiency around 17%, which is noticeably higher than approximately 0.4% from an SC that is dedicated to producing electricity.

Other approaches regarding environmental impact and economic advantages have also been made. Regarding the climate impact, the majority (around 60%) of the CO₂ emissions are generated by the power plants used during the construction phase, meaning that the SC’s production period has a low impact compared with its developing stage. Economically, the main conclusion that was obtained considered the construction and the design of the SC. That study indicated that it is less feasible to build one large-scale SC than several smaller ones due to the slight output difference between them. Furthermore, since combined SC systems have been proposed, one economic analysis indicated that this approach increases the system’s total net profit due to the rise of the working hours and number of outputs, presenting negative income values between the first and fourth years.

To point out the importance of numerical modeling to less-known forms of technology, one study analyzed a solar power plant with a short diffuser. Similar to a SC, this approach uses an updraft to turn a turbine and produce energy. As its main findings, the research indicated that the proposed technology could produce between 5.17 and 16.95 MW with wind speeds between 30 and 50 m/s. This paper's main contribution was to present preliminary results based on numerical modeling before any physical experimentation.

Previous studies are dominated by analysis focused on creating several outputs and studying the importance of SC’s structural designs. This work exploits solar radiation harvesting to obtain alternative and clean power generation using a technology that does not require specialized tracking systems or materials. Hence, the present study focuses on analyzing the influence that different types of storage systems have on the SC’s performance, including the possibility of using phase change materials (PCMs) to prolong and increase the energy production of the SC. The study’s main objective is to evaluate the influence that different storage materials have on an SC’s performance. To carry out the analysis, CFD is implemented using COMSOL Multiphysics from which essential parameters such as temperature, pressure, and wind speed are obtained.

### 2 | METHODOLOGY

Since there is a wide range of storage material options, two main types are evaluated: solids and PCMs. To narrow down the number of alternatives, the monthly average performance is initially analyzed, implementing a steady-state approach, after which the top two options of each type of material are
selected for time-dependent analysis in COMSOL to observe each material's behavior and influence on the SC’s performance throughout the day, including the weather and irradiation change during an average summer day in Qatar.

2.1 Model calculations

At first, the geometry and boundary conditions used to model the SC are defined. Since the system is based on the Spanish prototype, the dimensions of the structure used for its design are the same (see Table 1). Furthermore, for the steady-state simulations, boundary conditions for each model element are reflected in Table 2. The discretization scheme was considered linear for the heat transfer in solid and fluid modules, while P1 + P1 was implemented in the turbulent flow; this second scheme refers to solving fluid velocity and pressure field linear shape functions applied. Both are the default options for such studies in COMSOL.

Regarding Table 2, it is relevant to point out that solar radiation passes the transparent collector toward the ground; hence, this bottom layer’s surface is considered a heat source. Also, the heat storage layer properties depend on the type of material used to carry out the analysis. Furthermore, irradiance and ambient conditions are modified based on Qatar’s average summer day for the time-dependent simulation.

To carry out the numerical airflow simulation within the SC, the k-ε model is applied, in which the following equations are implemented:

\[ \rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla \cdot \left[ -p I + K \right] + F + (\rho - \rho_{ref}) g \]  

(1)

\[ K = (\mu + \mu_T) \left( \nabla u + (\nabla u)^T \right) - \frac{2}{3} (\mu + \mu_T) (\nabla \cdot u) I - \frac{2}{3} \rho k I \]  

(2)

\[ \rho \frac{\partial k}{\partial t} + \rho (u \cdot \nabla) k = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon \]  

(3)

\[ \rho \frac{\partial \varepsilon}{\partial t} + \rho (u \cdot \nabla) \varepsilon = \nabla \cdot \left[ \left( \mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} P_k - C_{2\varepsilon} \rho \varepsilon^2 \]  

(4)

### Table 1 Solar chimney geometrical dimensions

| Section                     | Dimension (m) |
|-----------------------------|---------------|
| Entrance height of the collector | 2             |
| Inner height of the collector          | 6             |
| Collector diameter           | 122           |
| Chimney height               | 200           |
| Chimney radius               | 5             |
| Storage layer thickness      | 5             |

\[ P_k = \mu_T \left[ \nabla u \cdot (\nabla u + (\nabla u)^T) \right] - \frac{2}{3} (\nabla \cdot u)^2 - \frac{2}{3} \rho k \nabla \cdot u \]  

(5)

where: \( u \) is velocity magnitude (m/s); \( \rho \) is density (kg/m³); \( g \) is gravity (m/s²); \( \mu \) is dynamic viscosity (kg/m s); \( \mu_T \) is the turbulent dynamic viscosity coefficient; \( F \) is force (N/m³); \( k \) is the turbulent kinetic energy (J/kg); \( \varepsilon \) is dissipation (W/kg); \( \sigma \) is the turbulent Prandtl number.

Also, since heat transfer between solid and liquid (air) is involved in the simulation, Equations (6) and (7) are used. These expressions consider each element’s density, the capacity at constant pressure, temperature, time, and heat to carry out the calculations.

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q \]  

(6)

\[ q = -k \nabla T \]  

(7)

Furthermore, using the parameters obtained from the CFD modeling, the power output obtained from the turbine is calculated by implementing Equation (8).

\[ \dot{W}_{Turbine} = \eta_{Turb} \cdot \Delta P \cdot \dot{v} \]  

(8)

where: \( \eta_{Turb} \) is the turbine efficiency. \( \Delta P \) is the pressure drop across the turbine. \( \dot{v} \) is the volume flow rate.

Once all the multiphysics and power calculations are executed, both energy and exergy efficiencies of the system are calculated based on the following equations:

\[ \eta_{EnSC} = \frac{\dot{W}_{Turbine}}{\frac{1}{4} \pi \cdot (D_{coll}^2 - D_{ch}^2) \cdot Q_{rad}} \]  

(9)

\[ \eta_{ExSC} = \frac{\dot{W}_{Turbine}}{\frac{1}{4} \pi \cdot (D_{coll}^2 - D_{ch}^2) \cdot Q_{rad} \cdot \left( 1 - \frac{T_0}{T_{sun}} \right)} \]  

(10)

where: \( \dot{W}_{Turbine} \) is the power generated by the wind turbine in kW. \( D_{coll} \) is the diameter of the collector in m. \( D_{ch} \) is the diameter of the chimney in m. \( Q_{rad} \) is the irradiation in W/m². \( T_0 \) is the reference temperature (300 K). \( T_{sun} \) is the sun’s temperature (5778 K).

Regarding the more specific time-dependent approach, in which values of \( Q_{rad} \) are equal to zero during several hours, Equations (11) and (12) determine the efficiencies of the system considering the heat storage system as the source of input energy. In these expressions, \( \dot{Q}_{HS} \) will change depending on the material used for the storage since it contemplates its total mass and heat capacity (Cp).

\[ \eta_{EnSCnight} = \frac{\dot{W}_{Turbine}}{\dot{Q}_{HS}} \]  

(11)
A grid independence study was carried out to complete the model analysis in which positive results were obtained. In this approach, three meshes were modeled (see Figure 1), and the values of pressure, temperature, and wind speed were compared. As a result of these simulations, the difference among the fine, normal, and coarse meshes was between 0% and 1%. These errors translate into just a 0.4 kW difference in the power output calculations.

2.2 Validation

To validate the model, three parameters (temperature, velocity, and pressure) are compared with literature based on a scenario with 400 W/m² of irradiance and a soil layer with the following properties: 

\[ C_{p,soil} = 2016 \text{ J/(kg K)}, \quad \rho_{soil} = 1700 \text{ kg/m}^3, \quad \lambda_{soil} = 0.78 \text{ W/(m K)} \].

For the first variable, Figure 2A,B shows how the temperature gradually increases the closer it gets to the center of the structure, obtaining values from 300 K in the entrance of the collector, up to 310.16 K at the chimney's entrance, while in literature, this area presents values between 308.65 K and 305.22 K, representing a maximum error of 1.6%. Also, the storage layer located underground presents a higher temperature due to its capacity to absorb heat; in this case, the simulation reflected a value between 337 K and 339 K near the chimney, while Xu et al. study obtained 343 K yielding a maximum error of 1.75%.

Regarding the wind speed, Figure 3B reflects the noticeable increase in this parameter between the entrances of the collector to the chimney's exit. Furthermore, Figure 3C highlights the behavior of the velocity in the chimney's entrance, increasing from 2.2 m/s up to values between 12.6 and 13 m/s just after the collector-chimney connection curve, following a gradual increase to values such as 13.82 m/s just after this point. Xu et al. presented a similar outcome, with results that increased from 1.90 m/s to 14.46 m/s, indicating a maximum error of 4.63%. Moreover, Figure 3A shows how there is a gradual reduction in the velocity near the chimney's wall, obtaining values such as 12.27 m/s, while Xu et al. reflected 13.31 m/s, which represents an 8.48% error.

| Section               | Type                | Value                                                                 |
|-----------------------|---------------------|----------------------------------------------------------------------|
| Collector inlet       | Pressure, temperature | \( P_{ambient} = 101 \text{ kPa}, \quad T_{ambient} = 300 \text{ K} \) |
| Collector's surface   | Glass wall          | \( q_0 = 0 \text{ W/m}^2 \)                                           |
| Chimney outlet        | Pressure             | \( P_{ambient} = 101 \text{ kPa}, \quad T_{ambient} = 300 \text{ K} \) |
| Chimney's surface     | Wall                | \( q_0 = 0 \text{ W/m}^2 \)                                           |
| Ground                | Heat source         | Irradiance = 460 W/m²                                                 |
Pressure values were also used as a form of validation. Figure 4A shows how there is a gradual decrease in this parameter from the collector’s entrance to the chimney’s origin. Furthermore, Figure 4B indicates how in the collector-chimney connection area, there is a higher decrease in its values, after which it increases. In the area shown in Figure 4B, the pressure is between $-34.72$ Pa and $-93.46$ Pa, while the Xu et al. model presents a range between $-34$ and $-95$ Pa, from which a maximum error of $1.65\%$ is calculated.

To complete the validation of the model, power generation is also compared with the literature. This output is obtained by implementing Equation (8), using the values from...
Table 3 to calculate the power production from the wind turbine located inside the chimney. Pressure drop and volume flow rates are taken from the simulation, while the turbine efficiency was attained from Xu et al.4

Combining Equation (8) with Table 3, a power output of 22.30 kW is obtained. Compared with approximately 22.50 kW obtained by Xu et al.,4 this value presents an error of 0.92%, confirming the model’s validity.

Based on the outcome indicated above, Table 4 reflects that the model, based on the compared variables, presents a maximum error of 1.75%.

3 | HEAT STORAGE BEHAVIOR COMPARISON

To select the most suitable type of material, which absorbs heat while maintaining its influence in the collector’s temperature increase, the behavior of several options is studied.

The solar chimney is modeled with each material to carry out this analysis, considering the monthly irradiance averages throughout a year, as indicated in Table 5.

3.1 | Solid materials

As a first approach, solid materials are considered for the heat storage layer. Table 6 reflects a wide range of thermophysical properties used to execute the simulations.

To analyze these materials’ influence, two parameters are compared, power production from the SC and the heat storage temperature. Furthermore, the energy and exergy efficiencies are also evaluated. Figure 5 indicates how the irradiance value influences the SC’s power generation trend; however, it also reflects how the material used in the ground can impact the output. Sandstone and sand present the best outcome, while the rest of the options constantly indicate lower values. The lowest output of 23.92 kW is obtained while using concrete in November, the month in which the irradiance value is the lowest throughout the year. Moreover, a 35.36 kW peak power is obtained in April while implementing sandstone as the heat storage material.

Figure 6 presents a similar trend as Figure 5, in which sandstone and sand offer more beneficial values than the rest of the materials. Furthermore, sandstone yields the highest mean values, with 345.96 K, and it also has the lowest performance month, with 339.71 K in November.

Regarding the efficiency behavior, Figure 7A,B shows how the energetic and exergetic efficiencies present an inverted trend compared with the power output. This result is due to the small difference that exists between power outputs with the irradiance variation. For sandstone, a 23.5% change in electricity production is originated from a 31.8% shift of the irradiance. So, since the energy source increase for the same SC is higher than the improvement in power production, the efficiency performance is appropriate. Also, despite the change in the trend, sandstone and sand continue presenting the best outcome, compared with the rest of the materials, yielding an average energy efficiency of 0.122% and 0.113%, regarding the exergy output 0.128% and 0.119%, respectively, was obtained.

Out of the seven solid materials studied, sandstone presents the highest value in all the parameters throughout the year, including 8 months over 30 kW of power production and 350 K of temperature underground, averaging 31.49 kW. Thus, it is the most suitable option for the heat storage section of the solar chimney. On the other hand, concrete is the least beneficial one, surpassing 30 kW and 350 K, only in 2 months of the year; also, its annual power production has an average of 27.41 kW, which is
approximately 13% lower than the electricity generated compared with sandstone.

### 3.2 Phase change materials

In this stage, the behavior of PCMs is analyzed based on their influence on both power production and heat absorption, using the monthly average of the irradiance in Qatar. The difference between PCMs and solid materials is that the latter presents only one set of parameters that do not depend on the temperature. Simultaneously, the first one changes its state and some of its thermophysical properties (depending on the material). Table 7 indicates the materials studied; in this table, there is a new parameter, which is the melting temperature ($T_m$). Also, since the PCMs are located below a concrete layer, a 0.92 emissivity value is used. Furthermore, the selected materials represent different types of PCMs: metallic, paraffin, nonparaffin, and salt hydrates; this spread is made to expand the comparison’s reach.

Regarding the PCMs behavior, the transition is assumed to occur smoothly within the transition interval, $\Delta T_{1\rightarrow2}$, as shown in Figure 8. This area has its origin at the phase change temperature between phase 1 and 2, $T_{pc,1\rightarrow2}$, which depends on the material.

Other parameters used for the PCM behavior are the heat capacity ($C_p$), the mass fraction ($\alpha_m$), and the thermal conductivity ($k$). These properties depend on a smooth function ($\theta$) which represents the fraction of phase before the transition. Additionally, $C_p$ also requires the latent heat from phase 1 to phase 2 ($L_{1\rightarrow2}$), which may change based on the PCM.

The following equations (where the indices 1 and 2 in- dicate a material in phase 1 or 2, respectively) were implemented to carry out such calculations:

$$C_p = \theta_1 C_{p1} + \theta_2 C_{p2} + L_{1\rightarrow2} \frac{\partial \alpha_m}{\partial T}$$  \hspace{1cm} (13)

$$\alpha_m = \frac{1}{2} \frac{\theta_2 - \theta_1}{\theta_1 + \theta_2}$$  \hspace{1cm} (14)

$$k = \theta_1 k_1 + \theta_2 k_2$$  \hspace{1cm} (15)

$$\theta_1 + \theta_2 = 1$$  \hspace{1cm} (16)

Similar to the analysis made for the solid materials, power production, storage layer temperature, and the SC efficiencies are used to study the influence of several PCMs. Figure 9 indicates how all the PCMs follow the irradiance trend with similar power outputs, being bismuth-lead-tin-cadmium and magnesium chloride hexahydrate the materials with the highest power production with an average of 27.46 kW. On the other hand, the lowest production is obtained by n-octadecane, lauric acid, and RT42, which yielded 0.22% less power.
Regarding the heat storage temperature, Figure 10 shows the irradiance's impact on this parameter. Furthermore, Figure 10 also reflects how bismuth-led-tin-cadmium presents the lowest value, while the rest of the PCMs have a similar behavior throughout the year. In this case, n-octadecane offers the highest yearly average with 346.03 K, which is 0.27% higher than the lowest mean temperature.

Based on the efficiency output, Figure 11A,B highlights the small difference among all the PCMs. The energy efficiency value shifts between 0.10% and 0.114%, while the exergy efficiency remains within 0.105% and 0.12%. These low efficiencies originate from the size that the SC is required to generate a low amount of electrical output. Based solely on the efficiencies, all the PCMs perform similarly, indicating that there is no obvious choice on which one has a better performance.

To select the best material option based on the results obtained from PCMs, all factors must be considered. Since there is no clear advantage regarding the efficiencies, the choice of which option is more beneficial depends on SC's objective. If the goal is to produce the highest amount of power, disregarding heat storage, bismuth-led-tin-cadmium, and magnesium chloride hexahydrate are the best alternatives. But, since the idea of using a heat storage system is to prolong the power production in moments where the irradiance is nonexistent, then the temperature underground is relevant to consider. In this case, magnesium chloride hexahydrate is the best choice, since it presents an elevated storage temperature while yielding more power than the rest of the PCMs.

3.3 Comparison between solid materials and PCMs

Since the principle is to produce the most power and conserve the highest temperature possible, three options from each material are selected and compared with choose the best option.

Figure 12 reflects how the solid materials have a better impact on power production than the PCMs, being sandstone, the one with the most significant influence, while...
both PCMs present the lowest outputs, with an average close to 13% lower than sandstone. Moreover, the yearly average obtained from the PCM’s (27.46 kW) is 6.13% smaller than the sand’s output, representing the lowest production from the selected solid materials. The power production differential is originated from the increase in the wind speed passing through the turbine; this is a consequence of the buoyancy effect conceived by the rise in temperature within the collector area. Since the Sandstone scenario emits the highest temperature, the results indicated above are coherent.

Concerning the efficiencies, despite consistently presenting low values, the difference among the storage material types is observed. The solid materials offer better performance than the PCMs achieving a minimum energy efficiency average of 0.113% from sand, while all the PCMs obtained 0.106% (see Figure 14A). The same
result was observed in the exergy efficiency, in which sand has an average value of 0.119%, while the PCMs achieved 0.112% (see Figure 14B). This outcome reflects the small difference between the energy productions of the PCMs; it also indicates that sandstone is the most beneficial option studied. However, it is crucial to note that this analysis is based on steady-state simulations, in which the ability to store heat for an extended period and discharge such heat while no irradiance is entering the SC is not considered.

### 3.4 Time-dependent behavior

The comparison made above is carried out to filter the best material options for the SC. However, that study is based solely on the outcome that originated from average irradiance values. Hence, a time-dependent approach is carried out in this section to observe the effect of the change in weather and irradiance on SC’s performance. From this perspective, Table 8 reflects the hourly irradiance values of an average summer day in Qatar, indicating the existence of sunlight between 4:00 AM and 6:00 PM.

Based on Table 8, the SC’s power output was calculated, obtaining the results reflected in Figure 15. This analysis concurs with the previous sections’ results, indicating that sandstone is the best option out of the four materials; yielding an average of 28.25 kW with a maximum of 57.09 kW obtained between 2:00 PM and 3:00 PM. On the other side, bismuth-led-tin-cadmium presents the lowest power production, generating 18.51 kW on average and presenting the lowest pick with just 36.17 kW, which is 36.64% lower than the highest sandstone value.

Regarding the heat storage temperature, Figure 16 underlines the temperature differential between sandstone and the rest of the materials, with an average of 333.71 K and a
pick value of 359.57 K around 2:30 pm. Sand represents the closest option to sandstone with a mean of 325.87 K and a maximum value of 347.63 K after 3:00 pm. On the other hand, bismuth-led-tin-cadmium is the storage material with the lowest heat value, with an average of 317.56 K and a maximum temperature of 337.1 K registered just before 2:00 pm. Other than each material's properties, the main reason for the temperature difference between solid and PCMs is that the latter requires a concrete cover (as indicated in 0) that reduces irradiation entering the storage layer. Hence, the heat to which the PCMs are exposed is lower than the solid materials.

From an efficiency perspective, Figure 17A,B reflects a low outcome. As discussed before, these results are logical due to the large surface required to create a small power output. However, the influence of the storage material is noticeable; for example, sandstone yields the highest power output and storage temperature; these results are also reflected in the efficiencies, since this material offers the highest efficiency average, with 0.47% for energy and 0.50% for exergy. Furthermore, Figure 17 also shows elevated values when the irradiation input is low (during sunrise and sunset); this is caused by an elevated power production with low input. For instance, at 4:00 am the power output is just
20% with an irradiance input that is 92% lower than the 5:00 AM values.

Considering the results obtained in both power generation and the HST, the relation between these values is noticeable. The capacity that the SC has to yield power is directly associated with the HST; this result is logical since this storage portion of the SC increases the temperature under the collector area, creating a rise in the wind’s velocity. Figure 16 reflects that, despite presenting the lowest average temperature, magnesium chloride hexahydrate has a 2.85% drop between the peak temperature (339.21 K) and the final hour value (329.51 K), representing the lowest decrease among the four materials; this option is followed by sand (3.91%), bismuth-led-tin-cadmium (6.73%), and sandstone (11.60%). So, contemplating only the low heat drop, magnesium chloride hexahydrate would be the best option; however, the deficient power generation and HST obtained by this PCM counteracts such capacity.

4 | CONCLUSIONS

The present study compares the influence of several heat storage materials on the SC performance using a case study based in Qatar. Two approaches are taken to carry out this analysis; first, a dozen storage materials are narrowed down...
by comparing the monthly average outcomes from solid and phase change materials. Then, the daily influence that the top options (two solid and two PCMs) have on the daily power production and HST conservation is compared and analyzed. Based on the results obtained, the following relevant findings are obtained:

- Out of all the solid materials analyzed, sandstone has the highest yearly power production with an average of 31.49 kW and a maximum monthly value of 35.36 kW in April. This option also presents the most elevated HST yearly mean with 352.42 K, obtaining its pick value in April with 358.92 K.
- The PCMs present similar outcomes; however, bismuth-lead-tin-cadmium and magnesium chloride hexahydrate are the more appropriate options since they present the highest power generation yearly average of 27.46 kW. Furthermore, out of these two PCMs, magnesium chloride hexahydrate has the highest HST yearly average with 346 K.

### TABLE 8
Hourly irradiance values of a sample summer day in Qatar

| Hour | Irradiance (W/m²) | Hour | Irradiance (W/m²) |
|------|------------------|------|------------------|
| 0    | 0                | 13   | 884.60           |
| 1    | 0                | 14   | 734.20           |
| 2    | 0                | 15   | 540.11           |
| 3    | 0                | 16   | 320.35           |
| 4    | 5.93             | 17   | 113.60           |
| 5    | 74.73            | 18   | 14.65            |
| 6    | 265.21           | 19   | 0                |
| 7    | 487.43           | 20   | 0                |
| 8    | 687.71           | 21   | 0                |
| 9    | 842.90           | 22   | 0                |
| 10   | 948.91           | 23   | 0                |
| 11   | 986.52           | 24   | 0                |
| 12   | 968.32           |      |                  |

### FIGURE 15
Hourly power production from the SC: comparison between PCM’s and solid materials

![Hourly power production from the SC: comparison between PCM’s and solid materials](image)

### FIGURE 16
SCs’ hourly heat storage temperature: comparison between PCM’s and solid materials

![SCs’ hourly heat storage temperature: comparison between PCM’s and solid materials](image)
The SC with PCM as a heat storage medium yields less power than solid materials, obtaining a 27.46 kW as the maximum yearly average, with a 30.75 kW peak in April for bismuth-lead-tin-cadmium. Furthermore, the HST values are also lower than the solid materials, with values around 346 K representing the highest yearly average.

On average, the overall efficiency of an SC is low (less than 1%). However, the heat storage material may increase this percentage based on a rise in the useful output. In this study, sandstone yielded the highest energy and exergy efficiency.

During low irradiance times of the day (sunrise and sunset), the SC efficiency increases because there is a noticeable reduction in the system’s input and a smaller decrease in the output.

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**Nomenclature**

- $C_p$: heat capacity at constant pressure (J/kg K)
- $D_{\text{Coll}}$: diameter of the collector (m)
- $D_{\text{ch}}$: diameter of the chimney (m)
- $K$: thermal conductivity (W/m K)
- $\Delta P$: pressure drop across the turbine (kPa)
- $Q_{\text{rad}}$: solar radiation (W/m$^2$)
- $T_0$: ambient temperature (K)
- $T_{\text{HS}}$: heat storage temperature (K)
- $T_{\text{Sun}}$: temperature of the Sun (K)
- $\dot{v}$: volume flow rate (m$^3$/s)
- $\dot{W}$: work rate (kW)

**Greek letters**

- $\varepsilon$: surface emissivity (W/mK)
- $\eta$: efficiency (%)
- $\rho$: density (kg/m$^3$)

**Acronyms**

- CFD: computational fluid dynamics
- HST: heat storage temperature
- PCM: phase-changing material
- SC: solar chimney

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**FIGURE 17** Comparison between PCM’s and solid materials efficiency outputs of the SC: (A) energy efficiency, (B) exergy efficiency
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