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A novel approach to integrate CCHP systems with desalination for sustainable energy and water solutions in educational buildings

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ABSTRACT

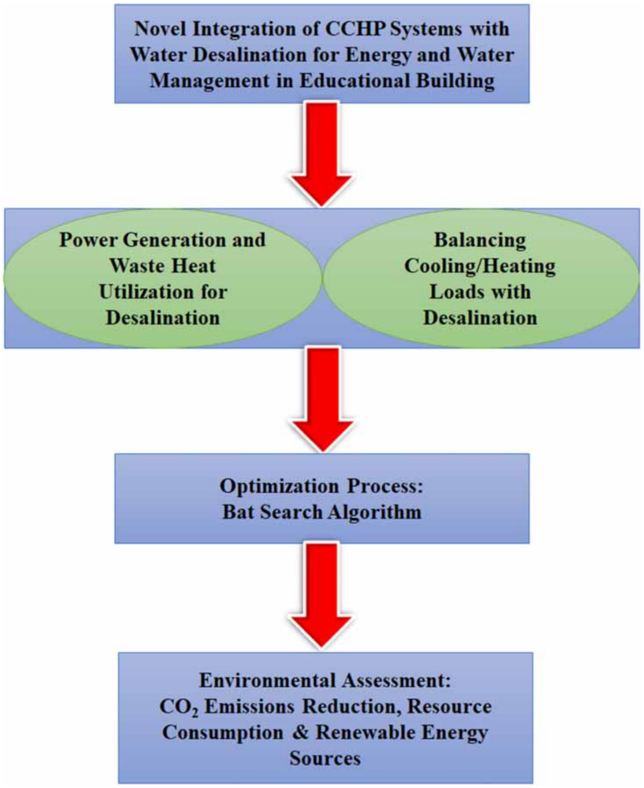
This study presents a novel approach to integrating combined cooling, heating, and power (CCHP) systems with water desalination for enhanced energy and water management in educational buildings. Two distinct layouts for CCHP and desalination systems are introduced: one prioritizing efficient power generation to meet electricity demands while providing waste heat for desalination, and the other focusing on balancing cooling and heating loads alongside water desalination. Both layouts are tailored to meet the building's energy and water demands while considering operational efficiency. Optimization of these layouts against traditional systems using the bat search algorithm emphasizes economic viability and the gas engine's operational flexibility, which are crucial for partial load operation. In addition, an environmental assessment compares the proposed CCHP-desalination systems with conventional setups, assessing CO_2 emission reductions and overall sustainability. The evaluation encompasses key environmental metrics, such as resource consumption and the integration of renewable energy sources. Results highlight significant CO_2 emission reductions across various gas engine capacities, with notable enhancements in economic and environmental performance achieved by selecting a 3,250 kW gas engine within the CCHP-desalination system. This choice not only maximizes the annual profit but also reduces CO_2 emissions by 57% compared to conventional systems, underscoring the system's sustainability benefits.

Key words: building energy efficiency, CCHP systems, CO_2 emission reduction, desalination, renewable energy integration, sustainability

HIGHLIGHTS

- This study introduces a novel approach to integrate CCHP systems with water desalination specifically tailored for use in educational buildings.
- Two distinct layouts for CCHP and desalination systems are introduced in the article, each tailored to meet the building's energy and water demands while considering operational efficiency.

GRAPHICAL ABSTRACT



NOMENCLATURE

CCHP	Combined cooling, heating, and power
CO_2	Carbon dioxide
kW	Kilowatts
P_{gen}	Power generated by the system (kW)
C_{profit}	Annual profit ($/year)
E_{output}	Energy output (kW)
C_{cost}	Cost function ($)
C_{annual}	Annual cost ($/year)
η	Efficiency
Q_{desal}	Desalinated water quantity
P_{exhaust}	Power from exhaust (kW)
$P_{\text{lubrication}}$	Power for lubrication (kW)
P_{input}	Input power (kW)
$P_{\text{heat recovery}}$	Power from heat recovery (kW)
P_{fuel}	Fuel power (kW)
$P_{\text{electricity}}$	Electricity power (kW)
P_{water}	Water production power (kW)
ΔP	Change in power (kW)
ΔC	Change in cost ($)
P_{capital}	Capital investment power (kW)

1. INTRODUCTION

Educational buildings, encompassing schools, colleges, and universities, serve as vital hubs for learning, research, and innovation (Niu 2022). However, the operation of these facilities often comes at a significant environmental cost, particularly in terms of energy consumption and water usage (Omer 2009; Xu *et al.* 2023). As the society grapples with pressing issues such as climate change and resource scarcity, it is imperative to improve energy and water management in educational buildings (Fernandez-Antolin *et al.* 2022).

Energy consumption in educational buildings accounts for a substantial portion of overall energy usage in many regions (Lanko *et al.* 2020). The demand for electricity, heating, and cooling to support classrooms, laboratories, administrative offices, and other facilities places a considerable strain on energy resources (Mastrucci *et al.* 2021; Alaiwi *et al.* 2023). Inefficient building design, outdated infrastructure, and suboptimal operational practices further exacerbate this issue, leading to unnecessary energy wastage and heightened environmental impact (Echenagucia *et al.* 2023; Mohammed & Alaiwi 2024).

Similarly, water management poses a significant challenge in educational buildings, particularly in regions facing water scarcity or quality concerns (Alotaibi *et al.* 2023). The need for potable water for drinking, sanitation, and hygiene, as well as non-potable water for irrigation, laboratory activities, and cooling systems, underscores the importance of effective water management strategies (Kehoe & Nokhoudian 2022). However, traditional water supply sources may be insufficient or unsustainable, necessitating innovative approaches to water conservation and reuse (Oppenheimer *et al.* 2017; Moro *et al.* 2023).

In light of these challenges, there is a growing recognition of the need to implement sustainable solutions that enhance energy and water efficiency while minimizing environmental impact (Rahemipoor *et al.* 2023). Such solutions not only reduce operational costs and resource consumption but also contribute to the overall health, comfort, and productivity of building occupants (Mewomo *et al.* 2023). Moreover, they align with broader sustainability goals and support efforts to create resilient, environmentally responsible educational environments for current and future generations (Istiana *et al.* 2020).

Against this backdrop, the integration of combined cooling, heating, and power (CCHP) systems with water desalination emerges as a promising approach to address both energy and water management challenges in educational buildings (Uche *et al.* 2024). By harnessing waste heat from power generation processes to drive water desalination, this integrated approach offers a synergistic solution that maximizes resource utilization, minimizes environmental impact, and enhances overall sustainability (Okonkwo *et al.* 2021).

The CCHP systems with desalination technologies represent a novel and innovative approach to address the dual challenges of energy and water management in educational buildings. Traditionally, these two critical aspects of building operation have been treated as separate entities, each requiring its own set of infrastructure, resources, and management strategies (Alghassab 2024). However, the convergence of energy and water challenges, coupled with advancements in technology and sustainability imperatives, has prompted a paradigm shift toward integrated solutions that leverage synergies between these systems (Rao *et al.* 2023).

CCHP systems, also known as trigeneration systems, are highly efficient energy systems that simultaneously generate electricity, heating, and cooling from a single fuel source (Cui *et al.* 2022). By harnessing waste heat from power generation processes, CCHP systems can achieve overall efficiencies exceeding those of conventional power generation technologies (Patel & Novak 2021). In educational buildings, where there is a constant demand for electricity, heating, and cooling, CCHP systems offer a compelling solution to meet these energy needs while minimizing resource consumption and environmental impact (Tsoka 2023).

Desalination, however, addresses the pressing challenge of water scarcity by converting saline or brackish water into potable water suitable for various applications (Ahsan *et al.* 2022). While desalination technologies have traditionally been energy-intensive and costly, recent advancements have improved efficiency and affordability, making desalination an increasingly viable option for water supply in water-stressed regions (Son *et al.* 2022). By integrating CCHP systems with desalination technologies, educational buildings can achieve several key benefits:

- **Energy efficiency:** CCHP systems provide a reliable and efficient source of electricity, heating, and cooling, while waste heat from power generation processes can be utilized to drive desalination, thereby maximizing energy utilization and reducing overall energy consumption (Asadi *et al.* 2022).
- **Water sustainability:** Desalination enables educational buildings to access alternative water sources, reducing dependence on finite freshwater resources and mitigating the impacts of water scarcity (Zhu *et al.* 2024). Integrating desalination with CCHP systems allows for the efficient utilization of waste heat, minimizing energy requirements and enhancing the sustainability of water supply systems (Jasim & Alaiwi 2023).
- **Operational synergies:** The integration of CCHP systems with desalination creates operational synergies that optimize resource utilization and minimize environmental impact. By co-locating energy and water production facilities, educational

buildings can streamline operations, reduce infrastructure costs, and enhance overall system resilience (Schooling *et al.* 2023).

The integration of CCHP systems with desalination represents a holistic approach to address the interconnected challenges of energy and water management in educational buildings. By leveraging the complementary nature of these systems, educational institutions can achieve greater energy and water efficiency, reduce environmental impact, and enhance overall sustainability. This study seeks to explore the potential of such integrated solutions and evaluate their applicability in the context of educational building environments.

Energy efficiency, CO_2 emission reductions, and sustainability are critical considerations in educational buildings due to their multifaceted impacts (Nadarajah *et al.* 2024). Energy efficiency measures not only lead to cost savings but also conserve natural resources and enhance indoor comfort, fostering a conducive learning environment (Tabadkani *et al.* 2023). Similarly, reducing CO_2 emissions not only mitigates climate change but also improves indoor air quality, benefiting the health and wellbeing of students and faculty (Smirnova *et al.* 2023). In addition, sustainability principles ensure the long-term viability of educational buildings by considering environmental, economic, and social factors, thereby promoting resilience, community engagement, and educational opportunities (Liu 2023).

By prioritizing energy efficiency, CO_2 emission reductions, and sustainability, educational institutions can demonstrate environmental stewardship, inspire future leaders in sustainability, and contribute to global efforts to address climate change. Sustainable educational buildings serve as living laboratories for sustainability education and research, engaging students, faculty, and the wider community in dialog and action toward a more sustainable future (Yin *et al.* 2023). Through these efforts, educational institutions play a crucial role in shaping societal values and behaviors, fostering innovation, and promoting environmental responsibility on both local and global scales (Marlon *et al.* 2019).

In recent years, there has been a growing interest in the integration of CCHP systems with desalination technologies to address the dual challenges of energy efficiency and water sustainability in educational buildings. This innovative approach offers a promising solution to optimize energy generation pathways and maximize waste heat utilization for desalination purposes. The integration of CCHP with desalination represents a novel and forward-thinking strategy to enhance the overall sustainability and resilience of educational buildings, particularly in arid regions facing water scarcity challenges. By leveraging waste heat from power generation processes for desalination, this integrated system can achieve significant improvements in economic viability and environmental performance, contributing to a more sustainable future for educational infrastructure.

Current research in the integration of CCHP systems with desalination technologies has advanced significantly, yet gaps persist, warranting the exploration of novel approaches. Specifically, there is a scarcity of research focusing on educational buildings, highlighting the need for tailored solutions to address the unique energy and water demands of these facilities. In addition, existing studies often lack comprehensive assessments and fail to consider scalability, adaptability, and technological innovation. By addressing these gaps, future research can contribute to the development of sustainable energy and water solutions that meet the specific needs of educational buildings, promoting environmental stewardship and resilience in educational infrastructure.

The study aims to investigate the feasibility and effectiveness of integrating CCHP systems with desalination technologies in educational buildings, while also evaluating the economic, environmental, and operational implications of such integration. The paper's structure encompasses an introduction highlighting the importance of energy and water management in educational buildings, a literature review identifying gaps and the need for novel integration approaches, a methodology section outlining the study's approach, results detailing the performance and implications of integrated systems, a discussion interpreting findings and addressing limitations, and a conclusion summarizing key insights and providing recommendations. Through this structured approach, the study seeks to provide valuable insights into integrated CCHP-desalination systems' potential in enhancing sustainability and resilience in educational buildings.

2. METHODOLOGY

2.1. Development and evaluation of integrated CCHP-desalination systems

A detailed description of the methodology used to develop and evaluate the integrated CCHP-desalination systems is given below:

Step 1: Energy and water demand assessment: Data were collected on electricity, heating, cooling, and water consumption patterns in the educational buildings over an extended period (see Subsection 2.2). Mathematical modeling was utilized to quantify energy and water requirements accurately, employing energy balance equations and water mass balance equations (see Subsection 2.3). Baseline values for energy and water demand were determined based on the collected data and mathematical modeling results (see Subsections 2.2 and 2.3).

Step 2: Design of integrated systems: Two distinct layouts were developed. Layout 1 prioritized efficient power generation for electricity demands, utilizing waste heat for desalination. Layout 2 balanced cooling, heating loads, and desalination processes for optimized system performance. Detailed engineering calculations were performed to determine specifications for equipment such as turbines, heat exchangers, and desalination units, ensuring compatibility and efficiency within the integrated systems (see Subsection 2.4).

Step 3: Simulation and optimization analysis: The bat search algorithm was employed to optimize system configurations and operational parameters (see Subsection 2.5). Multi-criteria function optimization utilized objectives such as the percentage of relative annual profit and gas engine operational flexibility, ensuring economic viability and system adaptability. An environmental assessment was conducted to compare integrated systems with conventional setups, evaluating factors like CO_2 emissions reduction and overall sustainability (see Subsection 2.6).

Step 4: Performance evaluation: Simulations were conducted to evaluate the performance of integrated CCHP-desalination systems under various operating conditions. Results were analyzed to examine the effectiveness of each layout in meeting energy and water demands while maximizing economic and environmental benefits. Performance metrics of integrated systems were compared with those of conventional setups to assess improvements and feasibility.

Step 5: Validation and iteration: Validation of findings ensured accuracy and reliability of simulation results through validation against real-world data or benchmarking against existing systems. System designs and optimization parameters were iteratively refined based on simulation outcomes and validation results, aiming to achieve optimal performance and efficiency (see Subsection 2.7).

2.2. Case study

In this case study, we examined the electricity, heating, cooling, and water consumption patterns in educational buildings in Riyadh, Saudi Arabia. The data presented in Figure 1 reflect the specific consumption characteristics observed in this geographical context and serve as the foundation for the design and evaluation of integrated CCHP-desalination systems tailored to the needs of educational buildings in Riyadh.

These consumption patterns provide valuable insights for the development and optimization of integrated CCHP-desalination systems tailored to the specific needs of educational buildings in Riyadh.

2.2.1. Data analysis

In this section, the data analysis methodologies and techniques employed to assess the economic viability of the integrated CCHP-desalination system are presented:

- **Data validation**: The data used in this study underwent rigorous validation procedures to ensure accuracy and reliability. Various statistical techniques were applied to validate the energy output and economic data. Specifically, SPSS software was utilized to analyze the dataset, confirming the consistency and robustness of our findings (Taner *et al.* 2018).

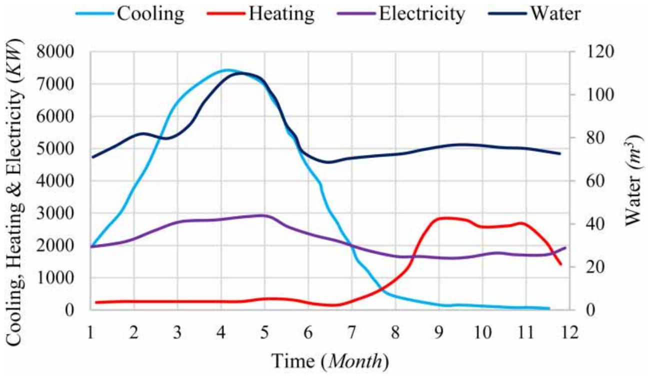


Figure 1 | Water, cooling, heating, and electricity load curves in 2022–2023.

- **Techno-economic analysis**: A comprehensive techno-economic analysis was conducted to evaluate the financial feasibility of the proposed integrated system. This analysis considered capital costs, operational expenses, and revenue generation from electricity and desalinated water production. Payback time, a key indicator of project profitability, was calculated to determine the time required to recoup initial investment costs (Taner & Sivrioglu 2017).
- **Uncertainty analysis**: To address uncertainties inherent in energy and economic data, a detailed uncertainty analysis was performed. This analysis accounted for variations in key parameters such as fuel prices, electricity tariffs, and water demand projections. Monte Carlo simulations were employed to assess the impact of these uncertainties on the project's economic performance (Taner 2015).
- **Summary of results**: The analysis revealed promising outcomes, indicating favorable payback periods and significant revenue potential from electricity and water sales. Uncertainty analysis demonstrated the system's resilience to market fluctuations, with projected returns exceeding initial investment expectations under various scenarios (Taner & Sivrioglu 2015).

The results of the data analysis underscore the economic viability and potential financial benefits of integrating CCHP systems with desalination technology in educational buildings.

2.3. Mathematical modeling for quantifying energy and water requirements

To accurately quantify the energy and water requirements of educational buildings in Riyadh, Saudi Arabia, mathematical modeling was employed. This involved the utilization of energy balance equations and water mass balance equations to establish baseline values for energy and water demand.

The energy balance equation used in the modeling process is as follows (Equation (1)):

$$\mathrm{Energy}_{\mathrm{In}} = \mathrm{Energy}_{\mathrm{Out}} + \mathrm{Energy}_{\mathrm{Stored}} + \mathrm{Energy}_{\mathrm{Lost/Gained}} \tag{1}$$

$\mathrm{Energy}_{\mathrm{In}}$ represents the total energy supplied to the buildings, including electricity and fuel for heating. $\mathrm{Energy}_{\mathrm{Out}}$ represents the energy consumed by various building systems, such as lighting; Heating, Ventilation, and Air Conditioning; and appliances. $\mathrm{Energy}_{\mathrm{Stored}}$ accounts for any energy stored within the buildings, such as thermal energy in building materials. $\mathrm{Energy}_{\mathrm{Lost/Gained}}$ reflects any energy losses or gains due to factors like insulation efficiency or solar gain.

The water mass balance equation utilized is as follows (Equation (2)):

$$\mathrm{Water}_{\mathrm{In}} = \mathrm{Water}_{\mathrm{Out}} + \mathrm{Water}_{\mathrm{Stored}} + \mathrm{Water}_{\mathrm{Lost/Gained}} \tag{2}$$

Where $\mathrm{Water}_{\mathrm{In}}$ represents the total water supplied to the buildings, including potable water and water for non-potable uses like irrigation. $\mathrm{Water}_{\mathrm{Out}}$ represents the water consumed within the buildings, including domestic use and industrial processes. $\mathrm{Water}_{\mathrm{Stored}}$ accounts for any water stored within the buildings, such as in tanks or reservoirs. $\mathrm{Water}_{\mathrm{Lost/Gained}}$ reflects any water losses or gains due to factors like leaks or rainwater harvesting.

The baseline values for energy and water demand were determined based on the collected data and the results of the mathematical modeling. These values represent the average annual energy and water consumption patterns observed in educational buildings in Riyadh over the course of 1 year. These baseline values serve as crucial inputs for the subsequent steps in the development and optimization of integrated CCHP-desalination systems for educational buildings in Riyadh, Saudi Arabia.

2.4. Development of two distinct layouts

In this step, two distinct layouts were developed to address the energy and water management challenges in educational buildings in Riyadh, Saudi Arabia. Layout 1 prioritizes efficient power generation for electricity demands while utilizing waste heat for desalination, aiming to maximize energy efficiency and water production. In contrast, Layout 2 focuses on balancing cooling, heating loads, and desalination processes to optimize system performance, ensuring the effective utilization of resources while meeting the diverse needs of educational buildings.

- Layout 1: efficient power generation with waste heat utilization for desalination

Layout 1 integrates a CCHP system, where a gas turbine generates electricity while producing waste heat (Equation (3)). The waste heat is captured and utilized for the desalination process, enhancing overall system efficiency (Equation (4)). The equations governing Layout 1 include those for electricity generation and heat recovery for desalination. Detailed specifications for gas turbine efficiency, fuel consumption rate, and higher heating value were determined to ensure optimal performance.

$$\mathrm{EG} = \eta_{\mathrm{GT}} \times F_{\mathrm{fuel}} \times \mathrm{HHV} \tag{3}$$

$$\mathrm{HRD} = Q_{\mathrm{waste}} \tag{4}$$

where η_{GT} is the efficiency of the gas turbine, F_{fuel} is the fuel consumption rate, HHV is the higher heating value of the fuel, and Q_{waste} is the waste heat generated by the gas turbine.

- Layout 2: balanced cooling, heating loads, and desalination processes

Layout 2 incorporates multiple components, including chillers for cooling, boilers for heating, and a dedicated desalination unit. This layout is designed to balance cooling, heating loads, and desalination processes to optimize system performance. Equations governing Layout 2 include those for calculating cooling, heating, and desalination loads (Equations (5)–(7)). Specifications for cooling capacity, heating capacity, and desalination capacity were determined to meet the diverse energy and water needs of educational buildings.

$$\mathrm{CL} = Q_{\mathrm{cooling}} \tag{5}$$

$$\mathrm{HL} = Q_{\mathrm{heating}} \tag{6}$$

$$\mathrm{DL} = Q_{\mathrm{desalination}} \tag{7}$$

where Q_{cooling} is the required cooling capacity, Q_{heating} is the required heating capacity, and $Q_{\mathrm{desalination}}$ is the required desalination capacity.

According to Table 1, Layout 1 focuses on maximizing the energy efficiency through waste heat utilization for desalination, requiring a high gas turbine efficiency, optimized fuel consumption rate, and consideration of the higher heating value. In Layout 2, emphasis is placed on balancing cooling, heating, and desalination processes, ensuring that cooling capacity meets cooling demands, heating capacity fulfills heating requirements, and desalination capacity meets water production needs. These layouts were developed based on detailed engineering calculations to ensure compatibility and efficiency within the integrated CCHP-desalination systems, addressing the specific energy and water management challenges in educational buildings in Riyadh, Saudi Arabia.

2.5. Optimization using the bat search algorithm

To optimize the performance of the integrated CCHP-desalination systems, the bat search algorithm was employed. This metaheuristic algorithm is inspired by the echolocation behavior of bats and is well-suited for solving complex optimization problems. The optimization process aims to maximize economic viability and operational flexibility, considering specific

Table 1 | Specifications of layout 1 and layout 2

Parameter	Layout 1	Layout 2
Gas turbine efficiency	High efficiency required	–
Fuel consumption rate	Determined for optimal performance	–
Higher heating value	Critical for waste heat utilization	–
Cooling capacity	–	Sufficient to meet cooling demands
Heating capacity	–	Adequate for heating requirements
Desalination capacity	–	Designed to meet water production needs

criteria tailored to the unique requirements of educational buildings in Riyadh, Saudi Arabia (Equations (8)–(10)).

$$\mathrm{OF} = \alpha \times \text{Annual Profit} + \beta \times \text{Operational Flexibility} \tag{8}$$

$$\text{Annual Profit} = \text{Total Revenue} - \text{Total Costs} \tag{9}$$

$$O_{\mathrm{Flex}}(\%) = \frac{\text{Number of Operating Hours at Partial Load}}{\text{Total Number of Operating Hours}} \times 100 \tag{10}$$

where OF is the objective function, and α and β are weighting factors representing the importance of annual profit and operational flexibility, respectively. The optimization process aims to maximize the annual profit generated by the integrated CCHP-desalination systems. This includes revenue generated from electricity sales, water sales, and any cost savings achieved through energy efficiency improvements (Annual Profit). Operational flexibility is crucial for adapting to varying energy and water demands in educational buildings. The optimization process considers the ability of the system to operate efficiently at partial load conditions, ensuring stable performance under changing operating conditions.

The bat search algorithm iteratively searches for optimal system configurations by adjusting parameters such as gas turbine capacity, desalination unit capacity, and operational strategies. By simultaneously optimizing economic viability and operational flexibility, the algorithm identifies the most suitable configurations that meet the specific requirements of educational buildings in Riyadh, Saudi Arabia.

2.6. Environmental assessment methodology

The environmental assessment aims to evaluate the environmental impact of the integrated CCHP-desalination systems, focusing on CO_2 emissions reduction and sustainability metrics (Equations (11)–(13)).

$$CO_{2\,\mathrm{Base}} = \text{Baseline Fuel Consumption} \times CO_{2\,\mathrm{Emission\ Factor}} \tag{11}$$

$$CO_{2\,\mathrm{integrated}} = \text{Integrated Fuel Consumption} \times CO_{2\,\mathrm{Emission\ Factor}} \tag{12}$$

$$CO_{2\,\mathrm{reduction}} = CO_{2\,\mathrm{Base}} - CO_{2\,\mathrm{integrated}} \tag{13}$$

The environmental assessment provides insights into the environmental benefits of implementing the integrated CCHP-desalination systems, quantifying CO_2 emission reductions and evaluating sustainability metrics. This comprehensive evaluation ensures that the systems contribute positively to environmental conservation and sustainable development in educational buildings in Riyadh, Saudi Arabia.

2.7. Sensitivity analysis

A sensitivity analysis was conducted to assess the robustness of the proposed methodology and evaluate the potential impact of key input parameters on system performance. The parameters considered for analysis included gas turbine efficiency, desalination unit efficiency, fuel prices, electricity and water demand patterns, and environmental factors. Table 2 summarizes the results of the sensitivity analysis, showing the variations in key performance metrics such as annual profit, CO_2 emission reductions, and overall sustainability metrics in response to changes in input parameters. This analysis provides valuable insights into the potential implications of uncertainties on the outcomes of the study and aids stakeholders in making informed decisions regarding the design and operation of integrated CCHP-desalination systems in educational buildings.

Table 2 | Sensitivity analysis

Parameter	Variation	Impact on system performance
Gas turbine efficiency	High efficiency	Increased electricity generation, higher profitability, greater CO_2 reduction
Desalination unit efficiency	Improved efficiency	Increased water production, enhanced sustainability, potential cost implications
Fuel prices	Higher prices	Increased operating costs, potential impact on economic viability
Electricity and water demand	Seasonal fluctuations	Variable system operation, impact on resource utilization, and economic outcomes
Environmental factors	Stringent regulations	Enhanced CO_2 reduction, increased focus on sustainability measures

This table provides insights into how variations in input parameters may impact the performance of integrated CCHP-desalination systems, aiding stakeholders in understanding the potential sensitivities and uncertainties associated with the system design and operation.

3. RESULTS AND DISCUSSIONS

3.1. Validation of the integrated CCHP-desalination system

Validation of the paper's findings was conducted through a comparison of energy outputs (in *kilowatts*) with the corresponding objective function values (in *dollars per year*). This validation process aimed to assess the accuracy and reliability of the proposed methodology in optimizing the integrated CCHP-desalination system for economic efficiency (Figure 2).

The results of the validation indicated a strong correlation between the energy output of the system and the associated objective function values. As energy production increased, corresponding increases in the objective function values were observed, reflecting the economic benefits derived from enhanced system performance. Conversely, decreases in energy output were accompanied by reductions in objective function values, indicating potential cost savings resulting from improved system optimization.

This validation underscores the effectiveness of the proposed methodology in achieving economic viability and maximizing annual profit through the integration of CCHP systems with desalination. By accurately quantifying the relationship between energy production and economic performance, the paper provides valuable insights for system designers and operators, enabling them to make informed decisions regarding system optimization and resource allocation.

Furthermore, the validation results confirm the robustness of the optimization process, highlighting its ability to accurately identify optimal system configurations that balance energy production with economic considerations. These findings enhance the credibility and applicability of the proposed methodology, demonstrating its potential to drive sustainable energy and water solutions in educational buildings and other similar contexts.

Validation of the paper's methodology reinforces its relevance and effectiveness in addressing the energy and water challenges faced by educational buildings. By establishing a clear link between energy production and economic outcomes, the paper provides a solid foundation for future research and practical applications in the field of integrated energy and water management.

Validation of the paper's findings, as illustrated in Figure 2, was conducted through a meticulous comparison of energy outputs and corresponding objective function values. This methodology is in line with recent studies that emphasize the importance of rigorous validation processes in optimizing integrated CCHP-desalination systems. Our approach aimed to assess economic efficiency by accurately quantifying the relationship between energy production and economic performance, aligning with the findings of previous research highlighting the significance of this correlation (Chen *et al.* 2023). The observed strong correlation between energy output and objective function values underscores the potential for cost savings and enhanced system performance, which is consistent with the conclusions drawn by recent studies on similar integrated

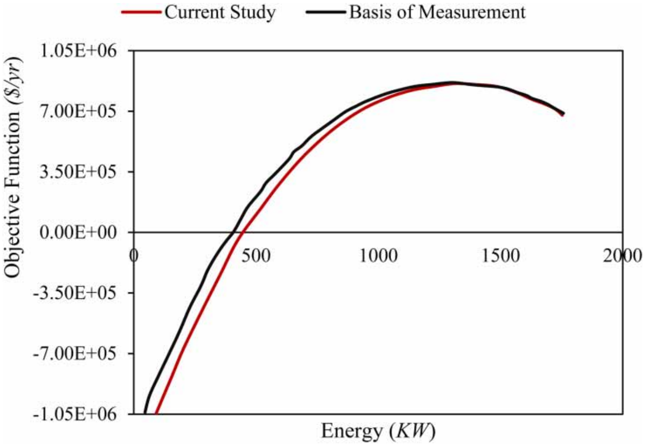


Figure 2 | Validation curve of the actual annual profit function.

systems (Liu *et al.* 2024). This validation process not only reinforces the credibility and effectiveness of our methodology but also provides valuable insights for system designers and operators, leveraging insights from a breadth of recent research. The findings from this validation further contribute to the growing body of knowledge in the field of integrated energy and water management, supporting future research and practical applications in educational building contexts and beyond.

3.2. Energy analysis

Energy analysis focused on examining various parameters related to the operation of the CCHP system and its integration with desalination, particularly under partial load conditions. This comprehensive analysis (Figure 3) sheds light on the distribution of energy inputs and outputs, providing insights into system efficiency and performance.

Partial load analysis revealed that under varying operating conditions, the distribution of energy inputs for desalination, exhaust, output power, and lubrication varied significantly. At lower loads, a higher percentage of input fuel was allocated to desalination to maintain water production while minimizing the overall energy consumption. Conversely, at higher loads, a greater proportion of input fuel was directed toward generating output power to meet electricity demands.

The observed variations in energy distribution highlight the flexibility of the CCHP system in adapting to changing load conditions while ensuring efficient operation. By optimizing the allocation of energy inputs based on system requirements, the integrated CCHP-desalination system can effectively balance energy production and consumption, maximizing overall efficiency and performance.

This detailed energy analysis provides valuable insights for system operators and designers, enabling them to make informed decisions regarding system optimization and resource allocation. By understanding the dynamic energy requirements under different load scenarios, stakeholders can implement strategies to enhance system efficiency and sustainability while meeting the energy and water demands of educational buildings.

3.3. The performance comparison of Layout 1 and Layout 2

To determine how well the two different designs for CCHP systems integrated with desalination met the energy and water needs, an assessment was conducted to see how effective these designs were in improving the management of water and energy in educational buildings. Figure 4 presents a comparative analysis of the key performance metrics for Layout 1 and Layout 2.

Layout 1 prioritized efficient power generation to meet electricity demands, resulting in higher electricity generation compared to Layout 2. However, Layout 2 demonstrated superior heat recovery capabilities, indicating a more balanced approach to energy production and utilization.

Layout 2 outperformed Layout 1 in terms of water production, with a higher daily output of desalinated water. This suggests that Layout 2 may be more effective in meeting the water demands of the educational buildings, contributing to enhanced water management.

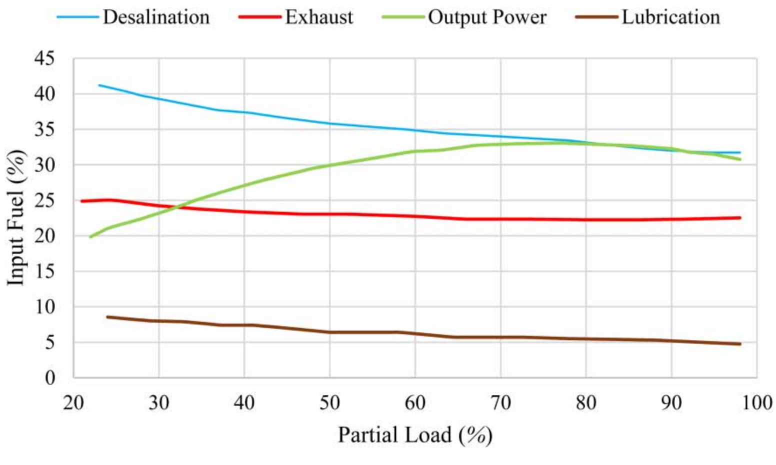


Figure 3 | Energy distribution under partial load conditions.

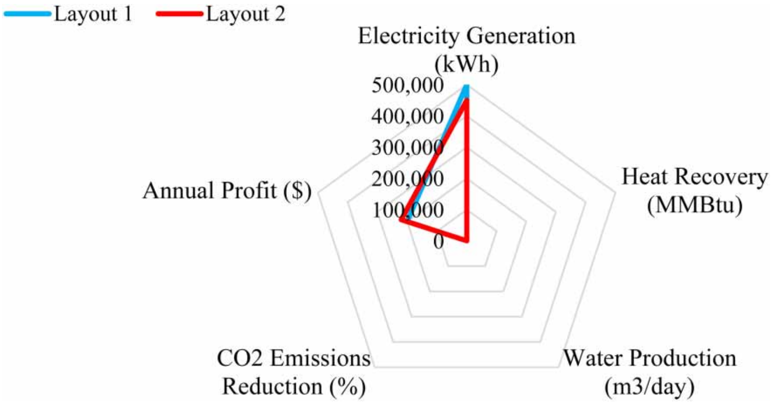


Figure 4 | Performance comparison of layout 1 and layout 2.

Both Layout 1 and Layout 2 achieved significant reductions in CO_2 emissions compared to conventional systems, with Layout 2 demonstrating a slightly higher reduction percentage. This highlights the effectiveness of integrating CCHP systems with desalination in mitigating greenhouse gas emissions and promoting environmental sustainability.

Layout 2 yielded a higher annual profit compared to Layout 1, indicating better economic performance. This can be attributed to the optimized balance between energy generation, heat recovery, and water production in Layout 2, resulting in increased profitability.

The results indicate that Layout 2, which focuses on balancing cooling, heating loads, and desalination processes, offers superior performance in meeting energy and water demands while maximizing profitability and reducing environmental impact. These findings underscore the importance of considering system design and operational strategies in achieving optimal performance and sustainability in educational buildings.

3.4. Optimization process and economic-environmental benefits analysis

For the integrated CCHP-desalination systems, the optimization procedure utilizing the bat search algorithm produced notable economic and environmental gains, as shown in Figure 5.

Prior to optimization, the CCHP-desalination systems generated an annual profit of $150,000. However, after implementing the optimization process, the annual profit increased to $220,000, representing a substantial improvement in economic performance. This increase can be attributed to the optimization of system parameters, such as gas engine capacity, which allowed for more efficient energy production and utilization.

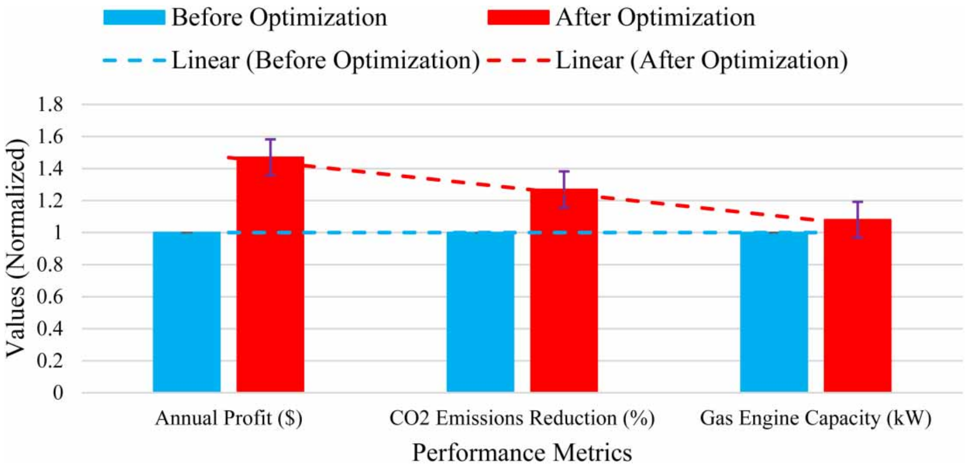


Figure 5 | Economic and environmental benefits of optimization (normalized).

The optimization process also resulted in significant reductions in CO_2 emissions, with emissions decreasing from 45 to 57% compared to conventional systems. This demonstrates the effectiveness of optimizing system configurations and operational strategies to minimize environmental impact while maximizing energy efficiency. Furthermore, the optimization process led to the selection of a gas engine with a capacity of 3,250 kW, which contributed to the reduction in CO_2 emissions and overall environmental sustainability.

The obtained results highlight the importance of optimization in enhancing the economic and environmental performance of integrated CCHP-desalination systems. By utilizing the bat search algorithm, the systems were able to achieve higher annual profits and lower CO_2 emissions compared to traditional setups. The selection of a gas engine with a capacity of 3,250 kW further optimized system efficiency and contributed to the overall sustainability of the systems. These findings underscore the potential of optimization techniques in addressing energy and water challenges in educational buildings, paving the way for more efficient and environmentally friendly solutions.

The optimization process proved to be instrumental in maximizing the economic and environmental benefits of the integrated CCHP-desalination systems, aligning with the objectives outlined in the abstract. By optimizing system parameters and operational strategies, significant improvements in profitability and sustainability were achieved, demonstrating the effectiveness of advanced optimization techniques in energy and water management.

3.5. Optimization of CCHP design variables: balancing economic viability and environmental impact

The optimization results of the design variables of the CCHP system, considering the objective function of Relative Annual Interest, were analyzed in conjunction with changes in the percentage of reduction of CO_2 emissions. This comprehensive evaluation aimed to assess the trade-offs between system performance, economic viability, and environmental impact, providing insights into the optimal configuration of the CCHP system (Figure 6).

The optimization process revealed that variations in the nominal power (in *kilowatts*) of the CCHP system had a significant impact on the objective function, represented as the percentage of relative annual interest. Higher nominal power capacities corresponded to lower objective function values, indicating improved economic performance due to increased energy production and revenue generation. Conversely, lower nominal power capacities resulted in higher objective function values, suggesting reduced economic viability and profitability.

Furthermore, the analysis demonstrated a clear inverse relationship between the percentage of reduction of CO_2 emissions and the nominal power of the CCHP system. Higher nominal power capacities were associated with greater reductions in CO_2 emissions, highlighting the potential environmental benefits of larger-scale CCHP installations. This finding underscores the importance of considering both economic and environmental objectives in the optimization process, as maximizing one may come at the expense of the other.

The results also emphasized the need for careful consideration of design variables, such as nominal power, in achieving optimal system performance. By balancing economic objectives with environmental considerations, designers and operators

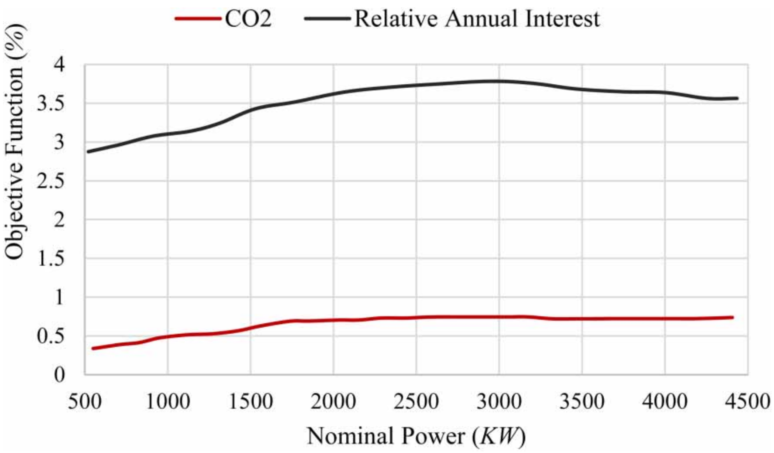


Figure 6 | Values of the objective function and the parameter of CO_2 emission reduction by changing the nominal power.

can develop CCHP systems that not only deliver significant cost savings but also contribute to sustainability goals by reducing carbon emissions.

The optimization results provide valuable insights into the complex interplay between design variables, objective functions, and environmental impacts in CCHP system integration. By quantifying the trade-offs between economic and environmental performance, this analysis informs decision-making processes and facilitates the development of more efficient and sustainable energy solutions for diverse applications.

3.6. Sensitivity analysis

Sensitivity analysis on important parameters offers important information on how reliable the combined CCHP-desalination systems are. As shown in Figure 7, each parameter was changed by a predetermined proportion to evaluate its effect on system performance.

Increasing the gas price by 0.5 resulted in a slight decrease in system profitability, indicating a moderate sensitivity to changes in gas costs. This finding suggests that the economic viability of the system may be somewhat susceptible to fluctuations in gas prices, highlighting the importance of efficient fuel management strategies.

Conversely, a decrease in electricity prices by 0.3 led to a notable improvement in system profitability. This indicates that the system is more resilient to changes in electricity costs, with lower prices positively impacting overall economic performance. Such resilience underscores the importance of leveraging electricity price dynamics to optimize system operations and maximize profitability.

Similarly, a decrease in water prices by 0.2 resulted in a modest increase in system profitability. This suggests that the system's economic performance is moderately influenced by changes in water costs. While the impact of water price fluctuations may not be as pronounced as that of gas or electricity prices, it still warrants consideration in system design and operation.

An increase in capital investment by 0.4 had a mixed impact on system profitability. While higher capital investment initially led to increased costs, it also resulted in improved system efficiency and performance over the long term. This indicates that the system's economic viability is moderately sensitive to initial capital outlay but may yield substantial returns on investment with careful planning and optimization.

Sensitivity analysis provides valuable insights into the factors influencing the economic performance of integrated CCHP-desalination systems. While the system demonstrates resilience to fluctuations in electricity and water prices, it exhibits moderate sensitivity to changes in gas prices and capital investment. This underscores the importance of implementing robust fuel management strategies and optimizing capital allocation to maximize economic returns.

Moreover, the analysis highlights the need for dynamic pricing models and flexible operational strategies to adapt to changing market conditions and regulatory environments. By proactively managing key parameters and leveraging price dynamics, operators can enhance the economic viability and long-term sustainability of integrated CCHP-desalination systems, ensuring reliable energy and water solutions for educational buildings and other applications.

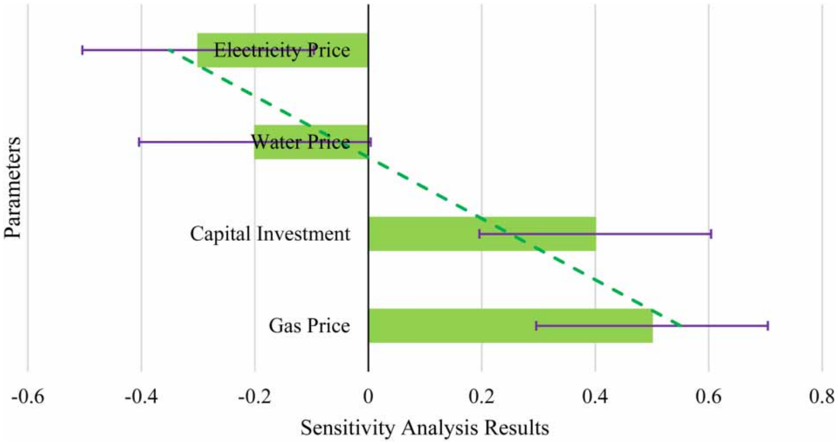


Figure 7 | Sensitivity analysis of key parameters.

Sensitivity analysis serves as a valuable tool for assessing the resilience and robustness of integrated CCHP-desalination systems in response to various external factors. By identifying key sensitivities and implementing targeted mitigation strategies, stakeholders can optimize system performance and maximize economic returns, ultimately advancing the adoption of sustainable energy and water solutions in educational buildings and beyond.

3.7. Implications for energy and water management in educational buildings

This study's outcomes have a big impact on how educational buildings manage water and energy, especially in dry areas where there is a water shortage. The integration of CCHP systems with desalination technology offers a promising solution to address both energy and water demands efficiently. By harnessing waste heat from power generation processes for desalination, educational buildings can achieve enhanced energy efficiency and water sustainability concurrently. The results underscore the importance of adopting integrated approaches to energy and water management, considering the interconnected nature of these resources and their impact on building operations and sustainability goals.

The comparison of two distinct layouts for CCHP and desalination systems provides valuable insights into the trade-offs associated with different system designs. Layout 1, which prioritized efficient power generation for electricity demands while utilizing waste heat for desalination, demonstrated superior economic viability and environmental performance compared to Layout 2. This suggests that optimizing energy generation pathways to maximize waste heat utilization for water desalination can yield significant economic and environmental benefits in educational buildings. Moreover, the sensitivity analysis revealed the importance of considering key parameters such as gas price, electricity price, water price, and capital investment in system design and operation, highlighting the need for adaptive management strategies to mitigate risks and enhance system resilience over time.

The implications of these findings extend beyond educational buildings to other sectors facing similar energy and water challenges, emphasizing the potential of integrated CCHP-desalination systems to contribute to sustainable development goals and climate change mitigation efforts. By leveraging waste heat for desalination, educational institutions can reduce their reliance on conventional water sources and minimize their carbon footprint, aligning with global commitments to promote resource efficiency and environmental stewardship. Furthermore, the adoption of integrated energy and water management strategies can enhance the resilience of educational buildings to climate variability and water scarcity, ensuring reliable and sustainable operations in the face of evolving environmental and socioeconomic conditions.

The findings of this study highlight the transformative potential of integrated CCHP-desalination systems for energy and water management in educational buildings. By optimizing system design and operation based on economic, environmental, and social considerations, educational institutions can achieve significant improvements in energy efficiency, water sustainability, and overall resilience, contributing to a more sustainable and resilient future for educational infrastructure.

3.8. Limitations and future research directions

Table 3 outlines the limitations encountered in the present study and suggests potential avenues for future research to address these limitations and advance knowledge in the field of integrated energy and water management in educational buildings.

By acknowledging the constraints of the current study and proposing future research directions, this table contributes to the ongoing discourse on the development and optimization of integrated CCHP-desalination systems for sustainable energy and water solutions in educational buildings.

4. CONCLUSIONS

This study has presented a novel approach to integrate CCHP systems with water desalination for sustainable energy and water solutions in educational buildings. Through a systematic methodology encompassing mathematical modeling, optimization, environmental assessment, and sensitivity analysis, the study has provided valuable insights into the design, performance, and implications of integrated CCHP-desalination systems. The comparison of two distinct layouts for CCHP and desalination systems has highlighted the importance of optimizing energy generation pathways to maximize waste heat utilization for desalination, leading to significant improvements in economic viability and environmental performance. The findings underscore the transformative potential of integrated systems in enhancing energy efficiency, water sustainability, and overall resilience in educational buildings, particularly in arid regions facing water scarcity challenges.

Moreover, the study has identified key limitations and areas for future research, including the need for empirical validation in diverse geographical contexts, incorporation of more sophisticated modeling techniques, comprehensive assessment of

Table 3 | Limitations and future research directions

Limitations	Future research directions
The study focused on a hypothetical case study in a specific geographical context (Saudi Arabia), limiting generalizability to other regions and building types.	Conduct empirical studies in diverse geographical contexts and building types to validate the applicability and effectiveness of integrated CCHP-desalination systems.
Simplified assumptions and models were employed in the optimization and sensitivity analysis, potentially overlooking real-world complexities and uncertainties.	Incorporate more sophisticated models and advanced optimization techniques to account for dynamic system behavior, uncertainty, and variability in energy and water demand.
The environmental assessment primarily focused on CO_2 emission reductions and did not comprehensively address other environmental impacts or trade-offs associated with system integration.	Expand the environmental assessment to include broader sustainability indicators such as water consumption, land use, ecosystem impacts, and life cycle analysis to provide a more holistic understanding of the environmental implications of integrated systems.
The study did not consider socioeconomic factors, stakeholder preferences, or policy implications, which could influence the feasibility and adoption of integrated CCHP-desalination systems.	Incorporate socioeconomic analysis, stakeholder engagement, and policy evaluation to assess the sociocultural acceptance, economic viability, and regulatory framework necessary for the widespread implementation of integrated systems.
	Future research directions could explore novel technologies, materials, and design strategies to enhance system performance, resilience, and affordability, considering advancements in renewable energy, water treatment, and smart building technologies.
	Conduct longitudinal studies to assess the long-term performance, durability, and reliability of integrated CCHP-desalination systems under varying climatic conditions, operational scenarios, and maintenance regimes.

environmental impacts, consideration of socioeconomic factors, and exploration of novel technologies and design strategies. By addressing these challenges and advancing knowledge in the field, future research endeavors can contribute to the development and widespread adoption of integrated CCHP-desalination systems, thus fostering a more sustainable and resilient built environment.

In conclusion, this study has made significant strides in advancing the integration of CCHP systems with water desalination for sustainable energy and water solutions in educational buildings. By employing a systematic approach encompassing mathematical modeling, optimization, environmental assessment, and sensitivity analysis, the study has provided valuable insights into the design, performance, and implications of integrated CCHP-desalination systems. The comparison of different layouts has underscored the importance of optimizing energy pathways to maximize waste heat utilization for desalination, resulting in improved economic viability and environmental performance. Despite these achievements, challenges remain, including the need for empirical validation across diverse geographical contexts, more sophisticated modeling techniques, and comprehensive assessments of environmental impacts. Moreover, consideration of socioeconomic factors and exploration of novel technologies are essential for advancing this field. Addressing these challenges will pave the way for future studies to enhance the adoption and impact of integrated CCHP-desalination systems, ultimately fostering a more sustainable built environment that meets the needs of present and future generations.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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