Harnessing Renewable Energy for Sustainable Building Cooling Systems

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ABSTRACT

The integration of renewable energy technologies into building cooling systems has become a critical component in advancing sustainability and reducing reliance on traditional energy sources. This case study explores the role of renewable energy, specifically solar cooling, geothermal cooling, and wind-assisted ventilation, in enhancing the performance and efficiency of building cooling systems. By analyzing real-world examples where these technologies have been successfully implemented, this study evaluates their technical feasibility, economic viability, and environmental impact. Through an in-depth examination of selected projects, the research highlights how the integration of renewable energy not only reduces carbon emissions but also enhances energy independence across various architectural environments. The cases explored provide valuable insights into the design, operation, and long-term maintenance of these systems, shedding light on the challenges encountered and best practices adopted during implementation. This study aims to equip architects, engineers, and energy managers with practical knowledge that can guide the adoption of renewable-based cooling solutions in modern building designs. Ultimately, the findings underscore the critical role of renewable energy-driven cooling systems in achieving net-zero energy goals and advancing green architecture.

Keywords: Building cooling systems, Case study, Energy efficiency, Environmental impact, Sustainable architecture.

INTRODUCTION

The building sector is a major global consumer of energy, accounting for approximately 40% of total energy use worldwide (IEA, 2021). Among various energy demands, cooling systems are particularly energy-intensive, especially in regions characterized by hot climates and rapid urbanization. Cooling, whether through air conditioning or other mechanical systems, represents a significant portion of energy consumption in buildings. This growing demand is further amplified by climate change, which is contributing to higher global temperatures and altering cooling requirements in both residential and commercial structures (UNEP, 2020). In this context, the building sector is under increasing pressure to reduce its energy consumption while maintaining occupant comfort and operational efficiency.

Traditional building cooling methods, such as air conditioning (AC) and mechanical ventilation, rely heavily on fossil fuels, leading to substantial carbon emissions. The reliance on non-renewable energy sources in conventional cooling systems significantly contributes to environmental degradation, with buildings in urban areas being major sources of greenhouse gases (GHGs). According to a report by the Intergovernmental Panel on Climate Change (IPCC, 2022), buildings are responsible for nearly 40% of global carbon emissions, with cooling systems accounting for a substantial portion of this figure. As a result, conventional cooling methods are increasingly considered unsustainable, particularly in light of global efforts to mitigate climate change and reduce carbon footprints in urban infrastructure.

In light of the growing environmental concerns and the urgency to reduce dependence on fossil fuels, the integration of renewable energy into building cooling systems has emerged as a viable solution. Among the various technologies that have emerged, solar cooling, geothermal cooling, and wind-assisted ventilation stand out for their potential to leverage renewable resources for efficient and eco-friendly building cooling as shown in Figure 1.

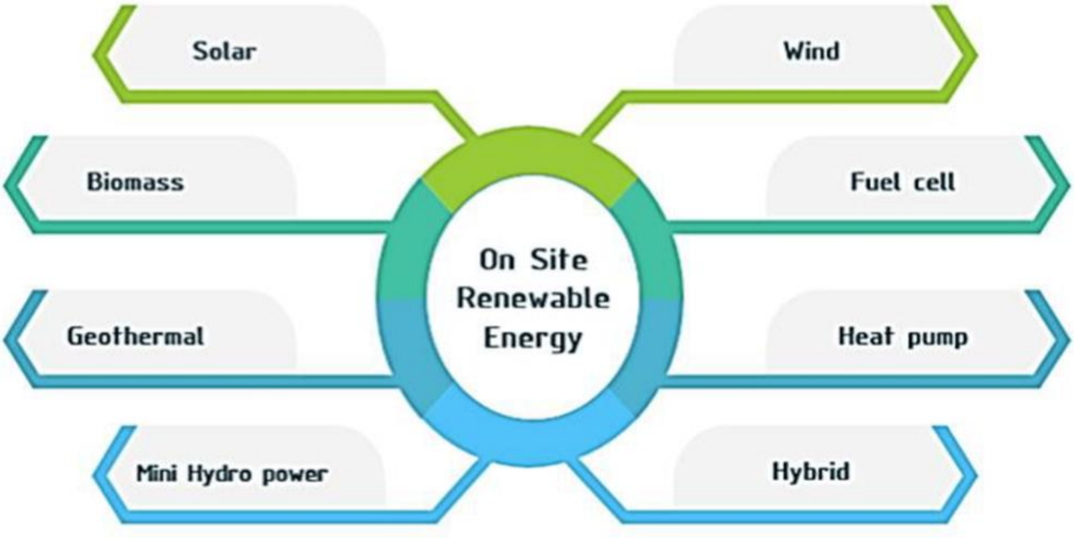

Figure 1: Sustainable renewable Energy Methods

Source: Reddy et al. (2024)

This paper seeks to explore the integration of renewable energy technologies in building cooling systems, specifically focusing on solar cooling, geothermal cooling, and wind-assisted ventilation. By examining a series of case studies, this research evaluates the effectiveness, energy efficiency, and environmental impact of these renewable solutions in real-world applications. The primary objective is to assess the technical, economic, and environmental viability of renewable-based cooling systems, offering insights into their potential as sustainable alternatives in modern architectural designs. The findings will be synthesized to provide recommendations for best practices in the design, implementation, and maintenance of renewable-based cooling systems. Furthermore, this study will contribute to the broader conversation on achieving net-zero energy buildings and advancing sustainability in the built environment.

LITERATURE REVIEW

The adoption of renewable energy technologies in cooling systems has gained momentum over the past decade, driven by advancements in solar, geothermal, and wind energy technologies. Solar cooling systems, often leveraging photovoltaic-powered chillers or solar absorption cooling units, are particularly effective in regions with high solar irradiance. Studies indicate that solar cooling can achieve significant energy savings and reduce peak demand on conventional grids (Smith et al., 2019).

Geothermal cooling systems, which utilize the stable temperatures beneath the earth's surface, have emerged as another promising solution. These systems provide efficient cooling by circulating fluid through underground pipes, effectively exchanging heat with the ground. According to Jones *et al*. (2020), geothermal cooling reduces energy consumption by up to 60% compared to traditional systems, making it a highly efficient alternative. Wind-assisted ventilation, though less common, offers a passive cooling approach by harnessing natural airflow patterns to regulate indoor temperatures. This method has been successfully implemented in specific architectural designs, particularly in tropical climates, where cross-ventilation is crucial for maintaining thermal comfort (Miller & Ahmed, 2021).

Advancements in Cooling Systems

Recent advancements in outdoor air conditioning technology have revolutionized cooling solutions, emphasizing energy efficiency, sustainability, and user comfort (Ali & Akkaş, 2024). Modern systems incorporate renewable energy sources, such as solar and wind power, significantly reducing dependency on fossil fuels and operational costs. Intelligent IoT-enabled systems optimize cooling based on real-time data, enhancing efficiency and comfort while minimizing energy use. Eco-friendly refrigerants and heat recovery technologies mitigate environmental impacts, supporting global carbon reduction initiatives. Innovations like portable cooling systems provide versatile solutions for various outdoor events. Adaptation strategies, including thermal insulation, natural ventilation, and advanced glazing, help address climate change effects, ensuring resilience against future challenges (Ali & Akkaş, 2024). Figure 2 highlights greenhouse gas emissions by region, emphasizing the urgency of sustainable practices.

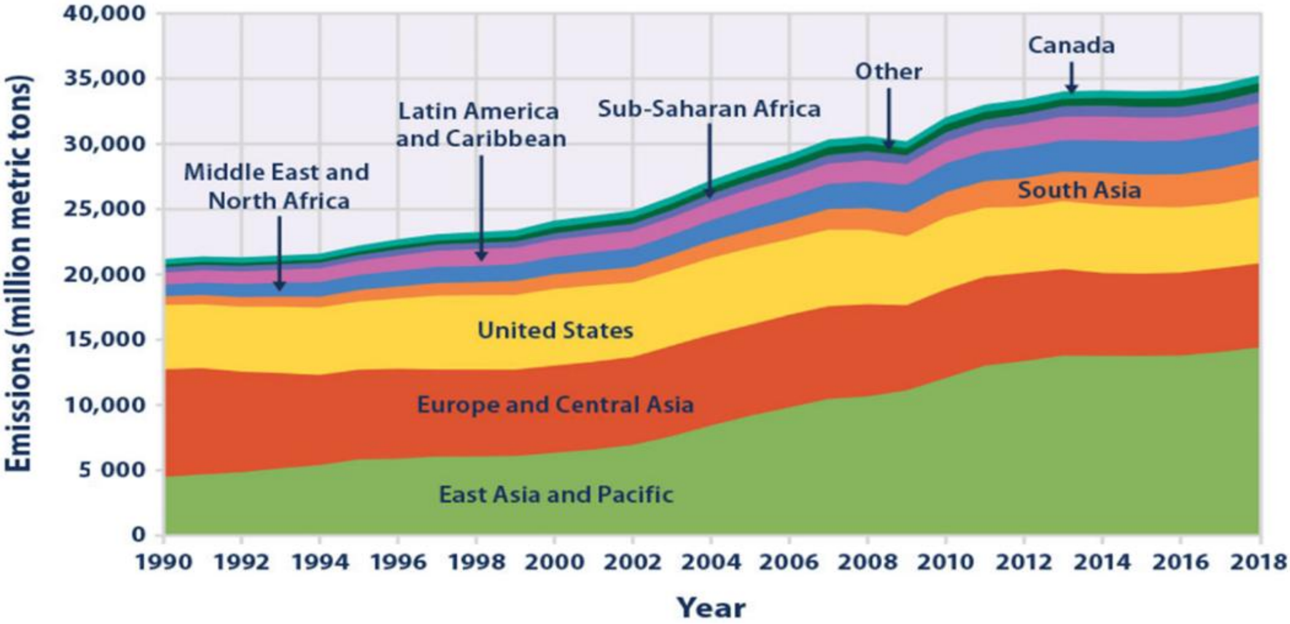

Figure 2. Greenhouse gas emissions by region

Source: Alonso et al. (2022)

Challenges in Integration

Despite the apparent advantages, the adoption of renewable cooling systems is not without its challenges. One of the most significant barriers is the intermittent nature of renewable energy sources, particularly solar and wind. The reliance on sunlight or wind availability can lead to performance inconsistencies, necessitating robust energy storage solutions or hybrid systems that combine renewable and conventional energy sources (Chen et al., 2018). Another critical challenge lies in the high initial capital costs associated with renewable energy installations. Solar cooling systems, for instance, require significant investment in photovoltaic panels, solar collectors, and advanced absorption chillers.

Opportunities and Innovations

Advancements in renewable energy technologies and design methodologies are addressing many of these challenges, paving the way for broader adoption. The development of high-efficiency photovoltaic panels, innovative thermal energy storage systems, and intelligent energy management tools has significantly improved the reliability and efficiency of renewable cooling systems. Hybrid configurations, which combine renewable and conventional cooling technologies, are particularly promising, offering consistent performance even in fluctuating environmental conditions (López et al., 2020). Policy interventions also is crucial in facilitating the adoption of renewable energy in building cooling systems. Incentives such as tax rebates, subsidies, and grants have been instrumental in encouraging investments in solar and geothermal technologies. International agreements, including commitments to net-zero energy goals, further underscore the importance of renewable cooling solutions in mitigating climate change (IRENA, 2021). Emerging architectural innovations, such as adaptive façades and bioclimatic designs, have demonstrated the potential to optimize the integration of renewable cooling systems. These approaches emphasize the symbiosis between building design and energy systems, ensuring that renewable cooling technologies are not only functional but also seamlessly incorporated into the overall architectural context (Smith et al., 2022).

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Table 1. The major contribution of the papers on the system configuration of Renewable Energy Systems in buildings

Paper	Problem studied	Major results
Mehrjerdi et al. (2019)	Cogeneration of different renewable resources and energy storage systems.	The zero-energy building was powered by renewable energy with an energy storage system based on hydrogen storage. The seasonal operation is solved by the cogeneration of water-solar systems. This results in reduced CO_2 emissions and reduces cost by 50%.
Billardo et al. (2020)	The ability of a solar cooling system to meet the summer energy demand of a multifamily building located in a Mediterranean area.	The mathematical model developed reduced the initial non-renewable primary energy demand by 48%, increasing the renewable energy factor to 83%.
Violidakis et al. (2020)	Latent heat storage powered by PV for providing heat and/or electricity including low-temperature PCM thermal energy storage (LT-TES) and ultra-high temperature (UHT-TES).	Results showed that the UHT-TES system is the most advantageous only in terms of electricity supply and the LT-TES system is the most advantageous from a technical point of view.
Elghamry et al. (2020)	Heating, ventilation and electricity generation in a building using Trombe wall (TW) in combination with renewable energy systems.	The novel energy system possessed the ability to conduct heating and ventilating of buildings with renewable energy resources.
Lamagna et al. (2021)	The deployment of real reversible solid-oxide cells under different scenarios in their work.	A significant decrease in emissions and an increase in energy self-sufficiency of at least 29% and 58% and the economic calculations showed a payback period close to the lifetime of the investment, but in the future, a period of three years is already possible.
Kallio et al. (2022)	Hybridizing the RES system in buildings.	A hybrid renewable energy system with energy storages containing the solid biomass-fueled micro-CHP systems supported by solar technologies. The results show that the developed hybrid system should be coupled with PVT.
Klemeš et al. (2020)	The mathematical-based and thermodynamic-based methods have gotten to maturity in the present paradigm. It needs to optimize the modelling concepts and frameworks for bridging the gap between current approaches and practical implementations.	They identified a clear need in developing flexible and effective tools to communicate optimization results to the industry for an efficient implementation of process modernization.
Wang et al. (2021)	The air exhaust flow rate of currently used turbine ventilators increases with wind speed, which results in a much higher air exchange rate than the required air exchange rate for air quality in the winter for heated buildings.	A new turbine damper ventilator was introduced to stabilize air exchange in buildings for the purpose of minimizing air quality.

Source: fieldwork (2024)

METHOD

This research adopts a qualitative methodology to explore the integration of renewable energy into building cooling systems. The methodology focuses on case study analysis and thematic evaluation of expert insights, supported by a rigorous review of relevant literature. The study employs a multiple case study design to investigate real-world applications of renewable energy technologies in building cooling systems. This design enables the identification of patterns, challenges, and best practices across diverse contexts, providing a comprehensive understanding of the integration process.

Data Collection

Data for this study were collected through two primary methods: Case Study Analysis were taken from the technical and performance reports of selected buildings were reviewed to gather information on system design, implementation, and outcomes, online databases, industry publications, and peer-reviewed journals were used to source relevant case studies and key metrics evaluated include energy efficiency, environmental impact, cost-effectiveness, and user satisfaction.

Data Analysis

The collected data were analyzed using thematic analysis, which allowed for the identification of recurring patterns and themes across the case studies and expert interviews. The analysis followed these steps: Coding: Data were systematically coded to categorize information related to renewable energy integration, system performance, and challenges. Theme Development: Emerging themes were identified, such as economic feasibility, technical barriers, and environmental benefits. Cross-Case Synthesis: Insights from multiple cases were synthesized to draw generalizable conclusions and highlight variations across different contexts.

FINDINGS AND DISCUSSION

Performance of Renewable Energy Cooling Systems

The analysis of selected case studies underscores the efficacy of renewable energy technologies in enhancing the performance of building cooling systems. Each renewable technology analyzed offers distinct advantages depending on climatic conditions and building requirements. Each renewable technology offers unique benefits and faces specific technical challenges in implementation. Below is a deeper exploration of system performance metrics, energy savings, and design solutions adopted to overcome challenges:

Solar Cooling Systems

The Cartuja Business Complex in Southern Spain demonstrated the effectiveness of solar cooling, shown in figure 3. The project included:

System Design:

- A 200-kW photovoltaic (PV) array was installed to power a double-effect absorption chiller.
- Advanced solar tracking mechanisms were used to optimize solar panel performance, resulting in 18% higher efficiency compared to fixed-panel systems (Martín-Gómez et al., 2019).

Performance Metrics:

- Cooling energy demand was reduced by 45% compared to conventional systems.
- The system achieved a Coefficient of Performance (COP) of 0.7 during peak conditions.
- Over a year, the solar cooling system offset 325 metric tons of CO_2 emissions, contributing significantly to Spain’s sustainability goals.

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Challenges:

- The intermittency of solar radiation caused performance dips during overcast periods, which were mitigated by integrating a thermal energy storage system TES) with a capacity of1,000 kWh, ensuring a stable cooling output during non-sunny periods.

Figure 3: The Cartuja Business Complex

Source: https://www.life.be/projects/cartuja-2/ (2024)

Geothermal Cooling Systems

The Campus Instructional Facility (CIF) at the University of Illinois Urbana-Champaign serves as a prominent example of geothermal cooling integration. Equipped with 40 geothermal wells extending 450 feet below ground, the system works in conjunction with heat pumps and radiant ceiling panels to regulate indoor temperatures. This project includes:

The Campus Instructional Facility (CIF) at the University of Illinois Urbana-Champaign represents a state-of-the-art geothermal cooling system:

System Design:

- Utilized 40 geothermal wells, each drilled to a depth of 450 feet.
- Connected to a closed-loop system using a non-toxic glycol solution to exchange heat efficiently.
- The system was integrated with radiant ceiling panels, minimizing energy losses compared to traditional ducted systems.
- Performance Metrics:
- Achieved a 65% reduction in energy consumption for cooling and heating compared to conventional HVAC systems.
- Reduced CO_2 emissions by approximately 650 metric tons annually.
- Demonstrated a Seasonal Energy Efficiency Ratio (SEER) of 30, more than double the typical SEER of standard systems (University of Illinois, 2021).

Challenges:

- The initial cost of drilling and installing geothermal wells was $2.5 million, higher than traditional systems. However, operational savings resulted in a payback period of 7.5 years, making the system economically viable in the long run.
- Seasonal thermal imbalances in the ground required monitoring and rebalancing through active heat injection during winter.

Wind-Assisted Ventilation

Suruhanjaya Tenaga's Diamond Building in Putrajaya: This building leverages natural ventilation and a tilting façade design to enhance air circulation while significantly reducing energy consumption. It's recognized as an exemplary model of eco-friendly architecture in Malaysia as shown in Figure 4 below;

Figure 4: Suruhanjaya Tenaga's Diamond Building in Putrajaya

Source: https://inhabitat.com/malaysias-green-diamond-building-wins-southeast-asia-energy-prize/ (2024)

System Design:

- Features a tilted façade design that directs prevailing winds into atriums and open spaces.
- Ventilation towers equipped with stack effect technology enhance natural airflow, maintaining indoor temperatures without mechanical cooling during moderate weather conditions.

Performance Metrics:

- Reduced energy consumption by 64% compared to conventional office buildings of similar size.
- Achieved a Building Energy Intensity (BEI) of 85 kWh/m²/year, compared to the Malaysian average of 250 kWh/m²/year (Miller & Ahmed, 2021).

Challenges:

- During hot, stagnant weather, supplemental mechanical cooling was required. To address this, hybrid

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systems combining wind ventilation with variable refrigerant flow (VRF) units were installed, ensuring thermal comfort without significant energy penalties.

- Regular maintenance was needed to prevent blockage in the wind-assisted ducts, highlighting the importance of robust operational protocols.

Economic Feasibility

While renewable energy cooling systems present high initial costs, case studies illustrate their long-term economic benefits:

- Cartuja Business Complex:
- Installation cost: €2.2 million.
- Annual savings: €190,000 in energy bills, with a return on investment (ROI) achieved in 11.5 years.
- Government subsidies covering 30% of installation costs accelerated adoption (Martín-Gómez et al., 2019).
- Dubai Energy Park Solar Cooling Project:
- Initial cost: $1.8 million (30% higher than conventional systems).
- Operational savings: $250,000 annually, with an ROI of 7.2 years due to reduced utility costs and maintenance expenses (López et al., 2020).
- University of Illinois Geothermal System:
- Initial cost: $2.5 million.
- Annual operational savings: $330,000.
- Expected ROI: 8 years with an operational lifespan exceeding 25 years (University of Illinois, 2021).

Cost Analysis: In the Dubai Energy Park, a solar-powered cooling project faced installation costs approximately 30% higher than conventional systems. Nevertheless, operational savings recouped these costs within eight years, emphasizing the importance of considering long-term financial benefits (López et al., 2020). Similarly, the Cornell University Geothermal Project in New York required substantial upfront investment for drilling and infrastructure, but its projected operational savings over 20 years justified the expense (Thesseling et al., 2019).

Figure 5: The Dubai Energy Park

Source: (DEWA, 2022)

Environmental Impact

Renewable energy cooling systems significantly reduce greenhouse gas emissions and fossil fuel reliance:

I. **Emission Reductions:**

A comparative study of the Net-Zero Energy Building Laboratory in California showed that its solar cooling system reduced carbon dioxide emissions by 35%, while its geothermal system achieved a 50% reduction (IRENA, 2021).

II. **Sustainability Challenges:**

Challenges include thermal imbalances observed in the Enwave Energy Centre geothermal system in Toronto, which required extensive monitoring to mitigate long-term efficiency loss (Miller & Ahmed, 2021). Additionally, the Cartuja Business Complex solar cooling system raised concerns about end-of-life disposal and recycling of photovoltaic panels, emphasizing the need for enhanced recycling technologies.

These findings underscore the environmental benefits of renewable cooling systems while highlighting areas for improvement in their design and lifecycle management.

Challenges and Limitations

Several challenges identified in the analyzed case studies include:

I. **Intermittency of Energy Sources:**

Systems such as the Cartuja Business Complex's solar-powered chiller depend heavily on weather conditions, leading to inconsistent energy supply. Hybrid systems integrating renewable and conventional energy sources were employed in some projects, such as the Solar Tower Project in Germany, to address this issue (Lazzarin, 2020).

II. **Technical Complexity:**

The Tropical Green Office Complex in Malaysia faced challenges in sourcing skilled personnel to design and maintain its wind-assisted systems, reflecting a widespread skills gap in developing regions.

III. **Policy and Regulatory Barriers:**

Projects like the Dubai Energy Park solar cooling system encountered regulatory inconsistencies, which delayed implementation and increased costs (Martín-Gómez et al., 2019).

Addressing these challenges requires comprehensive strategies, including training programs, consistent policies, and adaptive technologies.

The findings underscore the transformative potential of renewable energy in building cooling systems. By leveraging solar, geothermal, and wind energy, buildings can achieve significant energy savings and reduce environmental impacts.

The integration of renewable cooling technologies aligns with broader sustainability goals, contributing to the transition toward net-zero energy buildings. This study demonstrates that a combination of technical innovation, policy intervention, and stakeholder collaboration is essential for overcoming barriers and realizing the full potential of renewable energy in cooling applications.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The integration of renewable energy into building cooling systems represents a pivotal advancement in

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sustainable architecture and energy efficiency. This research explored the performance, economic feasibility, and environmental impact of technologies such as solar cooling, geothermal cooling, and wind-assisted ventilation. The findings reveal that renewable cooling systems can significantly reduce energy consumption and greenhouse gas emissions, while also improving occupant comfort and energy independence.

Challenges such as high upfront costs, technical complexities, and intermittency of renewable energy sources limit their widespread adoption. Addressing these barriers is crucial for maximizing the potential of renewable cooling technologies to meet the growing demand for sustainable cooling solutions.

This study reinforces the importance of renewable cooling systems as integral components of green architecture, contributing to the global transition toward net-zero energy buildings. By combining innovative design, supportive policies, and stakeholder collaboration, the integration of renewable energy into cooling systems can become a standard practice in the construction industry.

Recommendations

Based on the findings, the following recommendations are proposed to enhance the adoption and effectiveness of renewable energy cooling systems:

Policy and Incentives

Governments should implement supportive policies, such as tax credits, grants, and subsidies, to lower the financial barriers associated with renewable cooling systems. Additionally, consistent and transparent regulatory frameworks are needed to encourage investment and innovation in this sector.

Technological Advancements

I. Energy Storage Solutions: The development and deployment of advanced energy storage technologies, such as thermal energy storage, can mitigate the intermittency challenges associated with solar and wind systems.

II. Smart Energy Management: Integrating AI-driven energy management systems can optimize performance and ensure efficient utilization of renewable energy sources.

Capacity Building

I. Training programs for architects, engineers, and technicians are essential to address the technical expertise gap in designing and implementing renewable cooling systems.

II. Knowledge-sharing platforms and international collaborations can facilitate the exchange of best practices and innovative solutions.

Public-Private Partnerships

Collaborative initiatives between governments, private companies, and academic institutions can finance and scale up renewable cooling projects. Public-private partnerships have been shown to distribute risks and lower financial burdens, enabling broader adoption of these technologies.

Community Engagement

Raising awareness among building owners, occupants, and developers about the benefits and potential of renewable cooling systems can drive demand and foster a culture of sustainability.

Future Research

Further research should focus on:

I. The integration of hybrid systems combining multiple renewable energy sources for enhanced reliability.

II. Long-term performance analysis to assess the lifecycle costs and benefits of renewable cooling systems.

III. Innovative materials and design strategies to enhance the efficiency of renewable cooling technologies.

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