African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 4, Issue 2, April - June 2025
Page No: 78-87
Website: https://aaasjournals.com/index.php/ajapas/index
ISI 2024: 0.877 SJIFactor 2024: 6.752 معامل التأثير العربي: 1.62

Cooling with renewables: strategies for a green and efficient future

Muustafa Abdalla Othmam [1], Ail Dhaw Muftah Aljadi [2*], ahmed saleh Ibrahim Mohamed [3]
[1] Department of Refrigeration and Air Conditioning, Higher institute of engineering technology, Bani Walid, Libya
[2,3] Department of Electrical and Electronics Engineering, Faculty of Technical Sciences, Bani Walid, Libya

التبريد باستخدام مصادر الطاقة المتجددة: استراتيجيات لمستقبل أخضر وفعال

مصطفى عبد الله عثمان الرفروفي [1]، علي ضو مفتاح الجدي [2*]، أحمد صالح إبراهيم محمد [3]
[1] اقسم التكييف والتبريد، المعهد العالي للتقنيات الهندسية، بني وليد، ليبيا
[3،2] قسم الكهرباء والهندسة الالكترونية، كلية العلوم التقنية، بني وليد، ليبيا

[*]Corresponding author: ali.jadi86@gmail.com

Received: February 18, 2025	Accepted: April 14, 2025	Published: April 22, 2025

Abstract:
The global demand for cooling is rising rapidly due to population growth, urbanization, and climate change. Conventional cooling systems, which rely heavily on fossil fuels, contribute significantly to greenhouse gas emissions and energy inefficiency. This paper explores the potential of renewable energy sources to revolutionize the cooling sector, offering sustainable and efficient alternatives. By examining technologies such as solar-powered cooling, geothermal cooling, and bio-inspired designs, this study highlights strategies for integrating renewables into cooling systems. The paper also discusses policy frameworks, economic considerations, and future research directions to accelerate the adoption of green cooling solutions. The findings emphasize the urgent need for a transition to renewable-based cooling to mitigate environmental impacts and ensure energy security.

Keywords: cooling systems, climate change, renewable energy sources, adoption of green cooling solutions.

الملخص
يتزايد الطلب العالمي على التبريد بوتيرة متسارعة نتيجةً للنمو السكاني والتوسع العمراني وتغير المناخ. تُسهم أنظمة التبريد التقليدية، التي تعتمد بشكل كبير على الوقود الأحفوري، بشكل كبير في انبعاثات غازات الاحتباس الحراري وانخفاض كفاءة الطاقة. تستكشف هذه الورقة البحثية إمكانات مصادر الطاقة المتجددة في إحداث ثورة في قطاع التبريد، مقدمةً بدائل مستدامة وفعالة. من خلال دراسة تقنيات مثل التبريد بالطاقة الشمسية، والتبريد الحراري الأرضي، والتصميمات المستوحاة من المواد الحيوية، تُسلط هذه الدراسة الضوء على استراتيجيات دمج مصادر الطاقة المتجددة في أنظمة التبريد. كما تناقش الورقة أطر السياسات، والاعتبارات الاقتصادية، وتوجهات البحث المستقبلية لتسريع اعتماد حلول التبريد الصديقة للبيئة. تُؤكد النتائج على الحاجة المُلحة للانتقال إلى التبريد القائم على الطاقة المتجددة للتخفيف من الآثار البيئية وضمان أمن الطاقة.

الكلمات المفتاحية: أنظمة التبريد، تغير المناخ، مصادر الطاقة المتجددة، اعتماد حلول التبريد الخضراء.

Introduction
The world's cooling industry is at a turning point. By 2050, it is anticipated that cooling systems would need three times as much energy due to rising temperatures brought on by climate change and increased demand for refrigeration, air conditioning, and industrial cooling[1]. Conventional cooling systems contribute significantly to carbon emissions and energy inefficiency since they primarily use electricity produced from fossil fuels[2]. This

has increased interest in cooling systems based on renewable energy as a means of improving energy efficiency and decarbonizing the industry[3].
The cooling industry is at a crossroads, with significant opportunities and challenges ahead based on International Energy Agency (IEA) collected data [4]. The transition to more sustainable, efficient, and innovative cooling solutions is not only essential for mitigating climate change but also for meeting the growing global demand for cooling in a responsible manner. The industry's ability to adapt and innovate will be crucial in shaping a cooler, more sustainable future.
This paper aims to provide a comprehensive overview of renewable energy-driven cooling technologies, their potential, and the strategies required for their widespread adoption. By analyzing current trends, challenges, and opportunities, this study seeks to contribute to the discourse on sustainable cooling and inform policymakers, researchers, and industry stakeholders. The reaming sections in the article are organized as follows: Section 2 discussed the recently published high rank articles in the field of cooling systems with alternative sources in order to meet the load demand along with the side impacts on the environment with the provided solution and challenges. Section 3presented the following methodology in order to achieve the proposed objectives. Section 4 is placed the discussion of the cooling solar systems and geothermal cooling, and bio inspired system, conclusion. The results obtained is positioned and discussed in Section 5. The summary conclusion of the results and recommendationof the article is shown in the conclusion Section.The article ends with a list of recent up to date cited references.

1. Literature Review

1.1 The Growing Demand for Cooling

The demand for cooling is driven by multiple factors, including rising global temperatures, population growth, and increasing urbanization. The International Energy Agency (IEA) estimates that space cooling alone accounts for nearly 10% of global electricity consumption, with significant implications for energy systems and the environment[5].

1.2 Environmental Impacts of Conventional Cooling

Traditional cooling systems rely on vapor compression cycles, which consume large amounts of electricity and use refrigerants with high global warming potential (GWP)[6], [7]. These systems contribute to both direct emissions (from refrigerant leakage) and indirect emissions (from electricity generation).
the environmental impacts of conventional cooling systems involves identifying key factors such as energy consumption, greenhouse gas emissions, water usage, and refrigerant leakage. Table presents a textual representation of Environmental Impacts of Conventional Cooling Systems, while the Key Factors are:

1. Energy Consumption
2. Greenhouse Gas Emissions
3. Water Usage
4. Refrigerant Leakage

Table 1: Environmental Impacts of Conventional Cooling Systems Representation**.**

Environmental Impact	Low	Medium	High	Very High
Energy Consumption			X	
Greenhouse Gas Emissions		X		
Water Usage	X			
Refrigerant Leakage				X

1. **Energy Consumption**: Conventional cooling systems (e.g., air conditioners) are energy-intensive, often relying on fossil fuels, leading to **high** energy consumption.
2. **Greenhouse Gas Emissions**: These systems contribute to **medium** levels of greenhouse gas emissions due to energy use and refrigerant leakage.
3. **Water Usage**: Cooling systems like cooling towers use water, but the impact is generally **low** compared to other factors.
4. **Refrigerant Leakage**: Many conventional systems use refrigerators with high global warming potential (GWP), leading to **very high** environmental impact if leaked.

1.3 Renewable Energy for Cooling: Current State of Research

Recent studies have explored the integration of renewable energy sources, such as solar, geothermal, and wind, into cooling systems[8]. Solar thermal and photovoltaic (PV)-powered cooling systems have shown promise, particularly in regions with high solar irradiance. Geothermal cooling, which leverages the stable temperatures of the earth, has also gained attention for its efficiency and reliability. Based on the data collected from International Energy Agency by presenting the Global air conditioner stock in the period of 1990-2025 as illustrated in Figure 1[9].

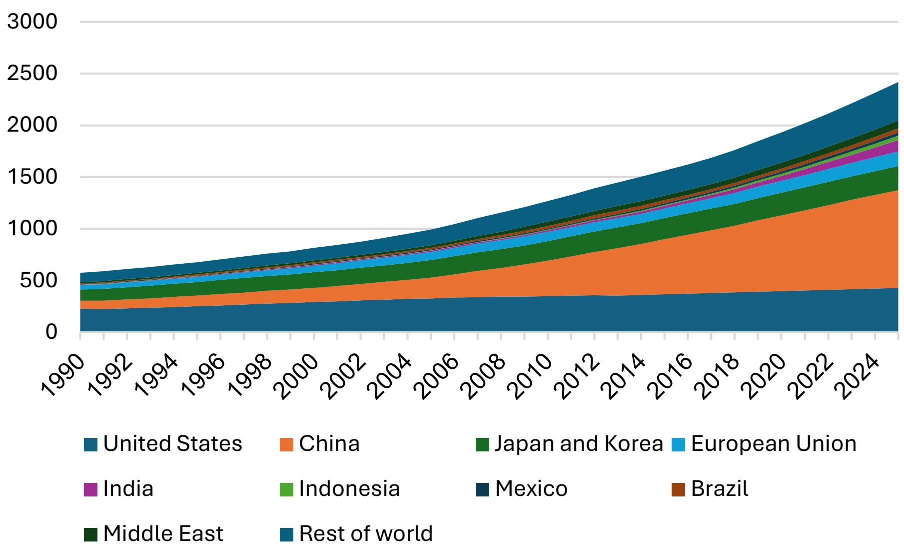


Figure 1: Global air conditioner stock, 1990-2025.

1.4 Barriers to Adoption

Despite their potential, renewable-based cooling systems face several barriers, including high upfront costs, technological limitations, and lack of awareness[10]. Policy and regulatory frameworks often lag behind technological advancements, hindering widespread adoption[11].

2. Methodology

This study employs a mixed-methods approach, combining a systematic literature review with case study analysis. Data was collected from peer-reviewed journals, industry reports, and government publications. Case studies of successful renewable cooling projects were analyzed to identify best practices and lessons learned. The findings were synthesized to develop a framework for integrating renewables into the cooling sector.
The methodology for navigating the turning point in the cooling industry involves a holistic approach that combines market analysis, stakeholder engagement, technological innovation, regulatory compliance, and continuous monitoring. By following this methodology, the industry can transition to more sustainable and efficient cooling solutions, meeting the growing global demand while minimizing environmental impact.
The methodology of the cooling industry being at a turning point involves a comprehensive approach that integrates technological innovation, regulatory compliance, market dynamics, and environmental considerations. The following methodology is tabulated in Table 2 consisting of the detailed breakdown of the methodology.

Table2: Followed methodology.

Methodology	Steps	Features
Assessment of Current State	Market Analysis	Conduct a thorough analysis of the current market, including demand trends, key players, and existing technologies.
	Environmental Impact Assessment	Evaluate the environmental impact of current cooling technologies, focusing on greenhouse gas emissions, energy consumption, and refrigerant leakage.
	Regulatory Landscape	Review existing and upcoming regulations related to refrigerants, energy efficiency, and environmental protection.
Identification of Key Drivers	Climate Change	Analyze how rising global temperatures and increasing frequency of heatwaves are driving demand for cooling solutions.
	Technological Advancements	Identify emerging technologies such as smart cooling systems, magnetic refrigeration, and advanced materials.
	Policy and Incentives	Understand the role of government policies, subsidies, and international agreements (e.g., Kigali Amendment) in shaping the industry.

Stakeholder Engagement	Industry Collaboration	Engage with manufacturers, suppliers, and industry associations to gather insights and foster collaboration.
	Government and NGOs	Work with policymakers and non-governmental organizations to align industry practices with regulatory requirements and sustainability goals.
	Consumer Awareness	Conduct surveys and focus groups to understand consumer preferences and awareness regarding sustainable cooling solutions.
Technological Innovation and R&D	Research and Development	Invest in R&D to develop new cooling technologies that are more energy-efficient and environmentally friendly.
	Pilot Projects	Implement pilot projects to test and validate new technologies in real-world conditions.
	Partnerships	Form partnerships with academic institutions and research organizations to leverage cutting-edge research and innovation.
Regulatory Compliance and Standards	Adoption of Low-GWP Refrigerants	Transition to refrigerants with lower global warming potential (GWP) in compliance with international agreements.
	Energy Efficiency Standards	Ensure that new products meet or exceed energy efficiency standards set by regulatory bodies.
	Certification and Labeling	Obtain certifications and labels that indicate compliance with environmental and energy efficiency standards.
Market Transformation	Product Development	Develop and launch new products that incorporate sustainable technologies and meet consumer demand for energy-efficient cooling solutions.
	Supply Chain Optimization	Optimize the supply chain to reduce costs, improve efficiency, and minimize environmental impact.
	Marketing and Education	Launch marketing campaigns and educational initiatives to raise awareness about the benefits of sustainable cooling solutions.
Monitoring and Evaluation	Performance Metrics	Establish key performance indicators (KPIs) to monitor the effectiveness of new technologies and practices.
	Feedback Loops	Create feedback loops to gather data from consumers, stakeholders, and pilot projects, and use this data to make continuous improvements.
	Reporting	Regularly report on progress towards sustainability goals, including reductions in greenhouse gas emissions and improvements in energy efficiency
Scaling and Implementation	Scaling Successful Pilots	Scale up successful pilot projects to broader markets, ensuring that the solutions are viable on a larger scale.
	Global Expansion	Expand the reach of sustainable cooling solutions to developing countries and regions with high cooling demand.
	Continuous Improvement	Implement a culture of continuous improvement, regularly updating technologies and practices based on the latest research and market trends.

3. Discussion

3.1 Solar-Powered Cooling Systems

Solar energy is one of the most widely studied renewable sources for cooling. Solar thermal cooling systems use solar collectors to drive absorption or adsorption chillers, while PV-powered systems use electricity generated from solar panels to operate conventional vapor compression systems. Both approaches have demonstrated significant potential, particularly in sun-rich regions. The comparison of the cooling capacity with Solar Irradiance is demonstrated in Figure 2. While the Energy Consumption Comparison between solar power and traditional power is presented in Figure 3. The Reduction in Carbon Footprint is presented in Figure 4 for 5 years.

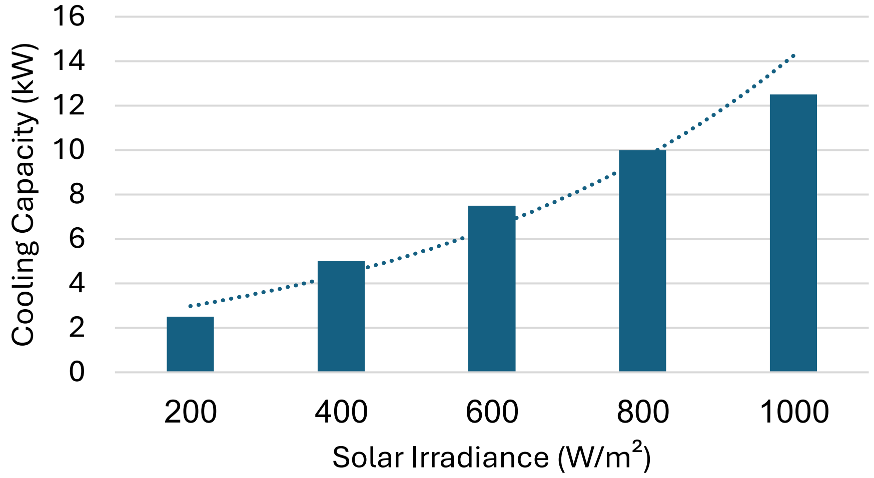


Figure2: Cooling Capacity vs. Solar Irradiance.

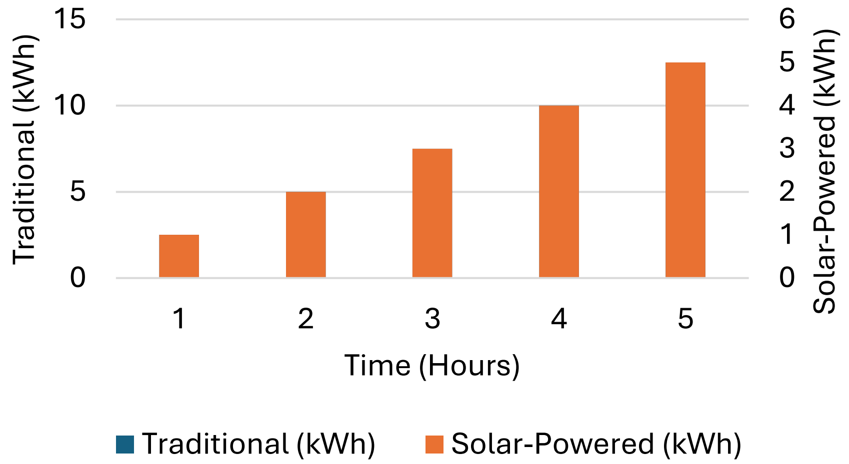


Figure3: Energy Consumption Comparison based on PV and traditional power.

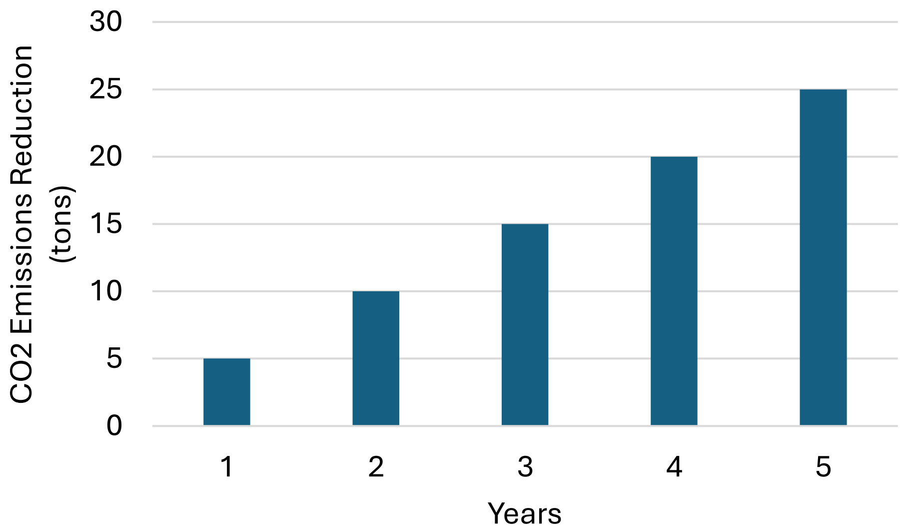


Figure 4: Reduction in Carbon Footprint.

3.2 Geothermal Cooling

Geothermal cooling systems utilize the earth's stable subsurface temperatures to provide efficient and reliable cooling. These systems are particularly suitable for large-scale applications, such as district cooling and industrial processes. The main comparison of the geothermal and traditional power is demonstrated in Figure 5.

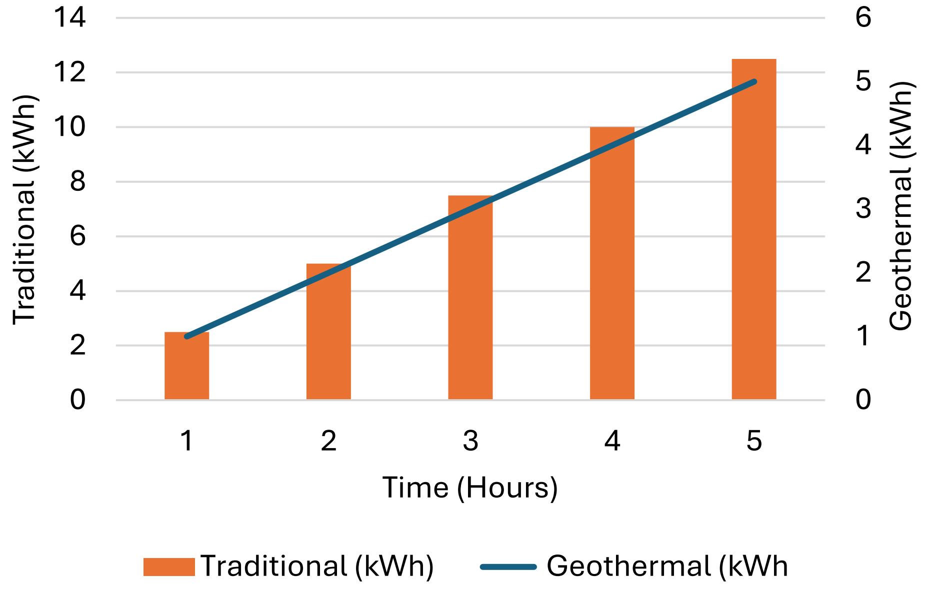


Figure5: Energy Consumption Comparison based on Geothermal and traditional power.

3.3 Bio-Inspired Cooling Designs

Nature-inspired cooling technologies, such as passive cooling techniques and biomimetic materials, offer innovative solutions for reducing energy consumption. Examples include evaporative cooling inspired by plant transpiration and radiative cooling materials that mimic the reflective properties of certain animal skins. The Energy Consumption Comparison between bio-inspired energy and international power is presented in Figure 6. Additionally, figure 7 shows thecooling efficiency vs. ambient temperature comparison.

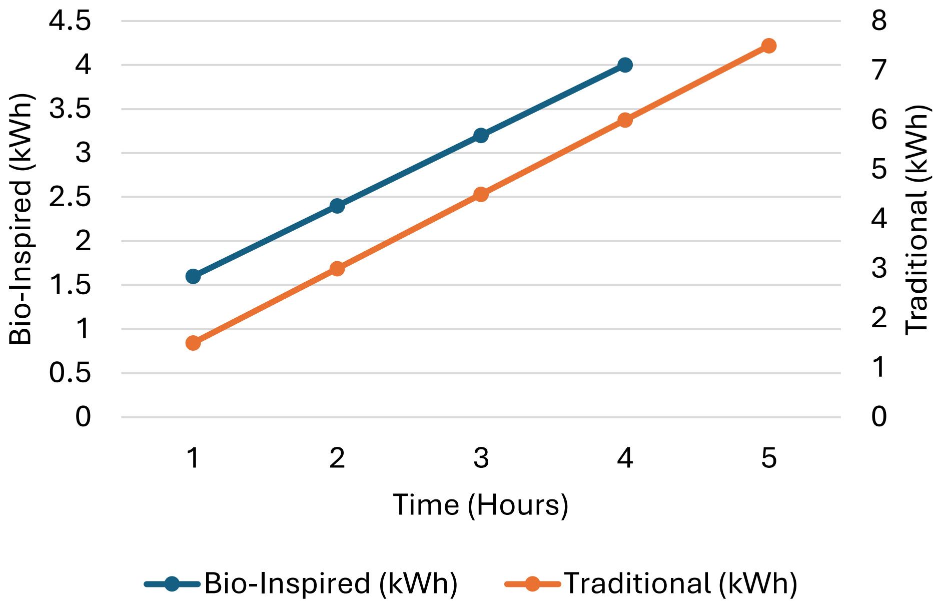


Figure 6: Energy Consumption Comparison between bio-inspired energy and international power.

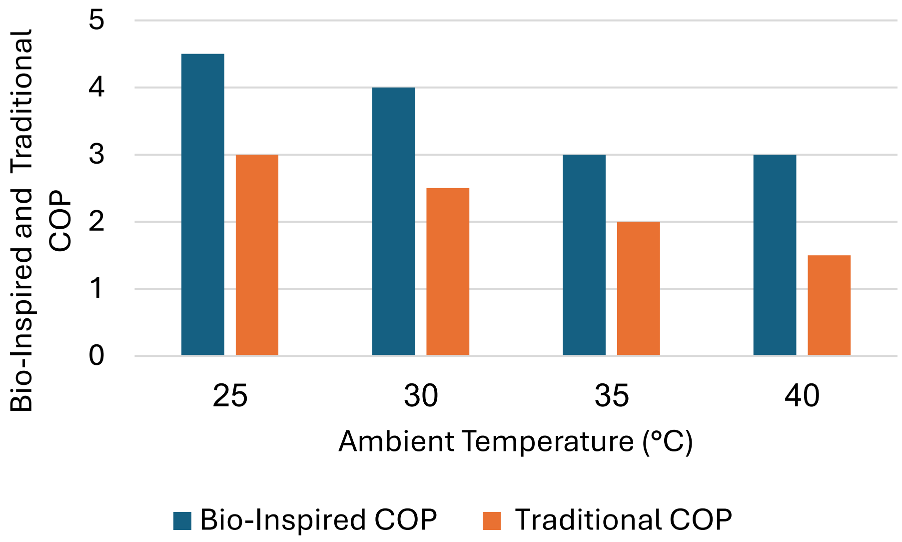


Figure 7: Cooling Efficiency vs. Ambient Temperature

3.4 Policy and Economic Considerations

The transition to renewable-based cooling requires supportive policy frameworks, including incentives for research and development, subsidies for renewable energy projects, and regulations to phase out high-GWP refrigerants[12]. Economic analyses indicate that while the initial costs of renewable cooling systems may be higher, their long-term benefits in terms of energy savings and environmental impact justify the investment.

3.5 Challenges and Future Directions

Key challenges include technological limitations, high upfront costs, and the need for skilled labor. Future research should focus on improving the efficiency and affordability of renewable cooling systems, as well as developing integrated solutions that combine multiple renewable sources.

3.6 Trends and developments

The cooling industry is indeed at a significant turning point, driven by several key factors that are reshaping its future. some of the most important trends and developments are presented in Table 3.

Table 3: Trends and developments of cooling system.

Trends and developments	Classifications	Explanation
Environmental Regulations and Sustainability	Phase-down of HFCs	The Kigali Amendment to the Montreal Protocol is driving the global phase-down of hydrofluorocarbons (HFCs), which are potent greenhouse gases. This is pushing the industry toward more environmentally friendly refrigerants like hydrofluoroolefins (HFOs), natural refrigerants (e.g., CO_2, ammonia, and hydrocarbons), and low-GWP (Global Warming Potential) alternatives.
	Energy Efficiency Standards	Governments and organizations worldwide are implementing stricter energy efficiency standards for cooling equipment, encouraging the development of more efficient technologies.
Technological Advancements	Smart Cooling Systems	The integration of IoT (Internet of Things) and AI (Artificial Intelligence) into cooling systems is enabling smarter, more efficient, and predictive maintenance solutions. These systems can optimize energy use and reduce operational costs.
	Advanced Materials	Innovations in materials science are leading to the development of more efficient heat exchangers and insulation materials, improving the overall performance of cooling systems
	Magnetic Cooling	Emerging technologies like magnetic refrigeration, which uses magnetic fields to achieve cooling, are being explored as potential alternatives to traditional vapor-compression systems.

Climate Change and Rising Demand	Increasing Global Temperatures	As global temperatures rise, the demand for cooling is increasing, particularly in regions that are experiencing more frequent and intense heatwaves. This is driving the need for more sustainable and scalable cooling solutions.
	Urbanization and Population Growth	Rapid urbanization and population growth, especially in developing countries, are leading to higher demand for air conditioning and refrigeration, putting pressure on existing infrastructure and energy systems.
Energy Transition and Decarbonization	Renewable Energy Integration	The shift toward renewable energy sources like solar and wind is influencing the cooling industry. Solar-powered air conditioning and refrigeration systems are becoming more viable, especially in off-grid or remote areas.
	Electrification	The push for electrification in various sectors, including transportation and heating, is also impacting the cooling industry. Electrically driven heat pumps, for example, are gaining popularity as a more efficient alternative to traditional heating and cooling systems.
Circular Economy and Waste Reduction	Recycling and Reuse	There is a growing emphasis on the circular economy within the cooling industry, with efforts to recycle and reuse materials from old or decommissioned cooling equipment. This includes recovering refrigerants and metals, reducing waste, and minimizing the environmental impact.
	Extended Product Lifespan	Manufacturers are focusing on designing products that are more durable and easier to repair, extending their lifespan and reducing the need for frequent replacements.
Policy and Market Shifts	Incentives and Subsidies	Governments and international organizations are offering incentives and subsidies to encourage the adoption of energy-efficient and low-GWP cooling technologies. This is helping to accelerate the transition to more sustainable cooling solutions.
	Consumer Awareness	Increasing awareness among consumers about the environmental impact of cooling systems is driving demand for greener products. This is pushing manufacturers to innovate and offer more sustainable options
Global Collaboration and Innovation	International Partnerships	Global initiatives and partnerships, such as the Cool Coalition led by the United Nations, are bringing together stakeholders from governments, industry, and academia to accelerate the transition to sustainable cooling.
	Research and Development	Increased investment in R&D is leading to breakthroughs in cooling technologies, from advanced refrigeration cycles to novel materials and systems that reduce energy consumption and environmental impact.

4. Results

The global demand for cooling is increasing at an unprecedented rate, driven by population growth, urbanization, and the escalating impacts of climate change. Traditional cooling systems, which predominantly rely on fossil fuels, are not only energy-intensive but also major contributors to greenhouse gas emissions, exacerbating the very problem they aim to mitigate. This paper delves into the transformative potential of renewable energy sources such as solar, geothermal, and bio-inspired technologies to revolutionize the cooling industry.

Table 4: Cooling Capacity vs. Renewable Energy Input.

Renewable Energy Input (kW)	Cooling Capacity (kW)
1	2
2	4
3	6
4	8
5	10

By harnessing these sustainable energy solutions, we can develop cooling systems that are both environmentally friendly and highly efficient. The study explores innovative strategies for integrating renewables into cooling infrastructure, emphasizing the importance of advanced technologies, supportive policy frameworks, and economic incentives. Furthermore, it highlights the critical role of research and development in overcoming existing challenges and scaling up these solutions. The findings underscore the urgent need for a global transition to renewable-based cooling systems to reduce carbon footprints, enhance energy security, and create a sustainable future. This transition is not just a technological shift but a necessary step toward mitigating climate change and ensuring long-term environmental and economic resilience.

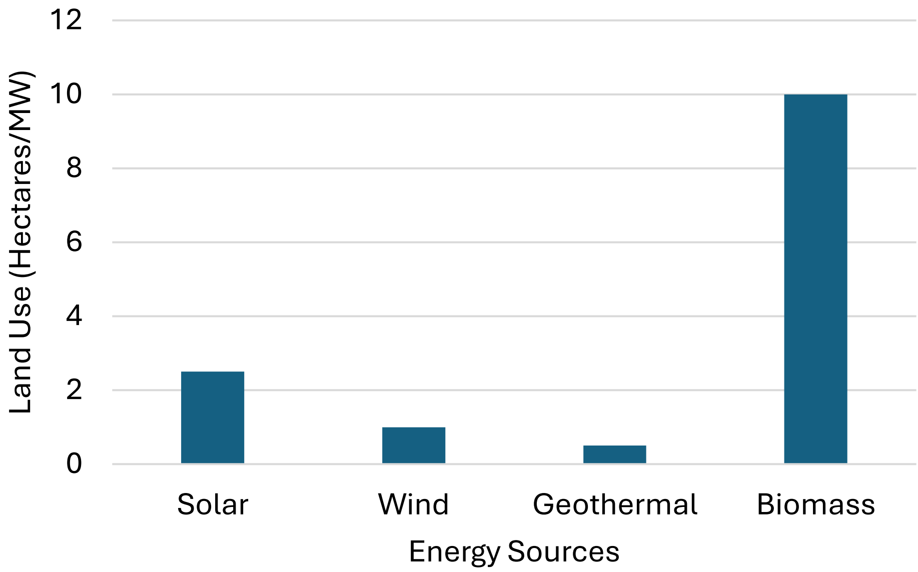
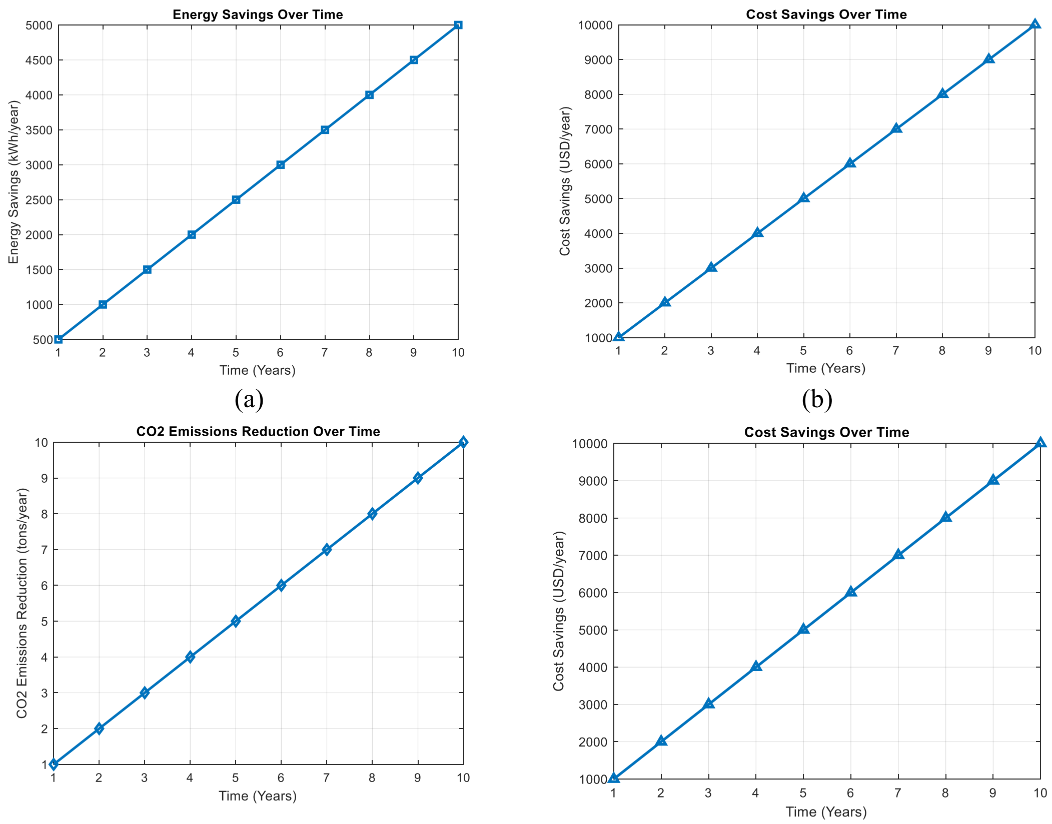


Figure 8: Land uses efficiently.

The provides a framework for visualizing the performance, environmental benefits, and economic savings of cooling systems powered by renewable energy. By customizing the data and parameters, you can analyze and present the results for your specific system, helping to demonstrate the advantages of renewable energy for a green and efficient future. It focuses on key metrics such as energy savings, CO_2 emissions reduction, and cost savings over time



(a) (b) (c) (d)

Figure 9: output results of energy and cost: (a) energy average over time, (b) cost saving over time, (c) CO_2 emission reduction over time, and (d) cost average over time.

Conclusion

The transition to renewable energy-based cooling systems is essential for achieving global climate goals and ensuring energy security. This paper has highlighted the potential of solar, geothermal, and bio-inspired cooling technologies, as well as the strategies needed to overcome barriers to adoption. Policymakers, researchers, and industry stakeholders must collaborate to accelerate the development and deployment of green cooling solutions. By prioritizing innovation, investment, and policy support, we can create a sustainable and efficient cooling sector for the future.

References

[1] Peter Efosa Ohenhen *et al.*, "Sustainable cooling solutions for electronics: A comprehensive review: Investigating the latest techniques and materials, their effectiveness in mechanical applications, and associated environmental benefits," *World J. Adv. Res. Rev.*, vol. 21, no. 1, pp. 957–972, Jan. 2024, doi: 10.30574/wjarr.2024.21.1.0111.

[2] A. Tabatabaeian, A. R. Ghasemi, M. M. Shokrieh, B. Marzbanrad, M. Baraheni, and M. Fotouhi, "Residual Stress in Engineering Materials: A Review," *Adv. Eng. Mater.*, vol. 24, no. 3, Mar. 2022, doi: 10.1002/adem.202100786.

[3] M. M. Khaleel, T. Mohamed Ghandoori, A. Ali Ahmed, A. Alsharif, A. J. Ahmed Alnagrat, and A. Ali Abulifa, "Impact of Mechanical Storage System Technologies: A Powerful Combination to Empowered the Electrical Grids Application," in *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, IEEE, May 2022, pp. 628–636. doi: 10.1109/MI-STA54861.2022.9837670.

[4] "Technology cost trends for wind turbine, 2015-2021," International Energy Agency (IEA). Accessed: Jan. 10, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/charts/technology-cost-trends-for-wind-turbine-2015-2021

[5] International Energy Agency (IEA), "Technical potential of selected renewable energy technologies for electricity generation," IEA, Paris. Accessed: Feb. 05, 2025. [Online]. Available: https://www.iea.org/data-and-statistics/charts/technical-potential-of-selected-renewable-energy-technologies-for-electricity-generation

[6] M. Kilic and M. Anjrini, "Comparative performance analysis of a combined cooling system with mechanical and adsorption cycles," *Energy Convers. Manag.*, vol. 221, no. July, p. 113208, 2020, doi: 10.1016/j.enconman.2020.113208.

[7] J. Zheng, L. Chen, X. Xu, L. Guo, Y. Zhou, and J. Wang, "A novel insulation system based on active cooling without power input for liquid hydrogen storage," *Energy*, vol. 182, pp. 1–10, Sep. 2019, doi: 10.1016/j.energy.2019.06.050.

[8] N. Emamdoost, A. Jafarian, and R. Kouhikamali, "Implementing multiple-effect distillation and reverse osmosis thermal coupling to improve desalination process performance in combined water and power plants," *Energy Convers. Manag.*, vol. 221, no. May, p. 113176, 2020, doi: 10.1016/j.enconman.2020.113176.

[9] International Energy Agency, "Electricity Information 2019 Final Edition Database Documentation," p. 88, 2019, [Online]. Available: www.iea.org/t&c/termsandconditions/

[10] J. A. Sanguesa, V. Torres-Sanz, P. Garrido, F. J. Martinez, and J. M. Marquez-Barja, "A Review on Electric Vehicles: Technologies and Challenges," *Smart Cities*, vol. 4, no. 1, pp. 372–404, Mar. 2021, doi: 10.3390/smartcities4010022.

[11] E. Costa, P. Wells, L. Wang, and G. Costa, "The electric vehicle and renewable energy: Changes in boundary conditions that enhance business model innovations," *J. Clean. Prod.*, vol. 333, no. December 2021, p. 130034, 2022, doi: 10.1016/j.jclepro.2021.130034.

[12] V. Oruç and A. G. Devecioğlu, "Experimental assessment of the retrofit of an internal heat exchanger in refrigeration systems: The effect on energy performance and system operation," *Appl. Therm. Eng.*, vol. 180, Nov. 2020, doi: 10.1016/j.applthermaleng.2020.115843.