Powering Cooling with Renewables: A Path to Sustainable Air Conditioning and Refrigeration

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تشغيل أنظمة التبريد بالطاقة المتجددة: الطريق نحو تكييف الهواء والتبريد المستدام

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Received: 20-04-2025; Accepted: 12-06-2025; Published: 22-06-2025

Abstract:
The worldwide need for air conditioning and refrigeration is increasing swiftly, propelled by climate change, urbanization, and economic expansion. Conventional cooling systems predominantly depend on fossil fuels and utilize refrigerants with significant global warming potential, hence intensifying the issue they aim to address. This publication examines the capacity of renewable energy to energize sustainable cooling systems, thereby diminishing greenhouse gas emissions and enhancing energy resilience. This article delineates a thorough approach to sustainable air conditioning and refrigeration through the analysis of technology developments, policy frameworks, and empirical case studies.

Keywords: conditioning and refrigeration, climate change, fossil fuels, renewable energy, sustainability.

الملخص:
تزداد الحاجة العالمية لتكييف الهواء والتبريد بسرعة، مدفوعة بتغير المناخ والتحضر والتوسع الاقتصادي. تعتمد أنظمة التبريد التقليدية بشكل رئيسي على الوقود الأحفوري وتستخدم مبردات ذات إمكانات عالية لظاهرة الاحتباس الحراري، مما يفاقم المشكلة التي تهدف إلى معالجتها. تناقش هذه المقالة قدرة الطاقة المتجددة على تشغيل أنظمة التبريد المستدامة، وبالتالي تقلي لانبعاثات غازات الاحتباس الحراري وتعزيز مرونة الطاقة. يقدم المقال منهجًا شاملاً لتكييف الهواء والتبريد المستدام من خلال تحليل التطورات التكنولوجية والأطر السياسية ودراسات الحالة العملية.

الكلمات المفتاحية: تكييف الهواء والتبريد، تغير المناخ، الوقود الأحفوري، الطاقة المتجددة، الاستدامة.

1. Introduction

1.1 The Cooling Paradox

Cooling is vital for human comfort, health, and economic efficiency. The energy-intensive characteristics of traditional cooling systems provide a paradox: as global temperatures escalate, the heightened reliance on air conditioning and refrigeration leads to greater energy consumption and greenhouse gas emissions[1]. The International Energy Agency (IEA) reports that cooling constitutes approximately 10% of worldwide electricity use, a proportion anticipated to quadruple by 2050[2].

This paradox demonstrates that various obstacles fossil fuel subsidies, regulatory challenges, financial constraints for grid operators, and insufficient or ineffective support policies and targets continue to hinder the extensive adoption of solar energy[3]. Consistent policies grounded in explicit, long-term objectives are crucial for efficiently harnessing the vast potential of solar energy[4].

Healthy economic expansion, combined with dynamic population, urbanisation and industrialisation growth, will see India’s role in global oil markets rapidly increase towards 2030, with significant implications for its oil trade balances, climate ambitions and energy security goals[5].

1.2 The Need for Sustainable Cooling

To break this cycle, the cooling industry must transition to sustainable practices. Renewable energy offers a viable solution by providing clean, abundant, and cost-effective power for cooling systems[6].

The contribution of this article examines how renewable energy can be integrated into air conditioning and refrigeration, highlighting the technological, economic, and policy measures needed to achieve this transition. The remaining section of the article is organized as follows: Section 2 the environmental impacts and carbon conventional cooling with its subsection. Section 3 discussed the renewable energy solution for cooling. The high-techsustainable cooling technologies presented in Section 4. The policies and economic considerations are tabulated in Section 5. Section 6 presented the case study along with the success stories of powering the systems by considering renewable systems. The acquired results are presented and discussed in Section 7. The challenges faced challenges and future direction are presented and explained in Section 8. Finally, the article ends with summarizing the conclusion of the study followed by the list of recent cited articles from the literature.

2. The Environmental Impact of Conventional Cooling

2.1 Energy Consumption and Carbon Emissions

Conventional cooling systems are highly energy-intensive, relying on electricity generated from fossil fuels. In 2020, air conditioning alone was responsible for approximately 1 billion tons of CO_2 emissions globallyto be reduced as in Figure 1 [7].

Figure 1:CO_2 emissions reduction[8].

New opportunities to use carbon dioxide (CO2) in the development of products and services are capturing the attention of governments, industry and the investment community interested in mitigating climate change as well as in other factors, including technology leadership and supporting a circular economy[9]. This analysis considers the near-term market potential for five key categories of CO2-derived products and services: fuels, chemicals, building materials from minerals, building materials from waste, and CO2 use to enhance the yields of biological processes[10]. As cooling demand grows, so does the strain on energy grids and the environment. The Global energy-related CO2 emissions by fuel for the period of 2000 to 2018 is shown in Figure 2.

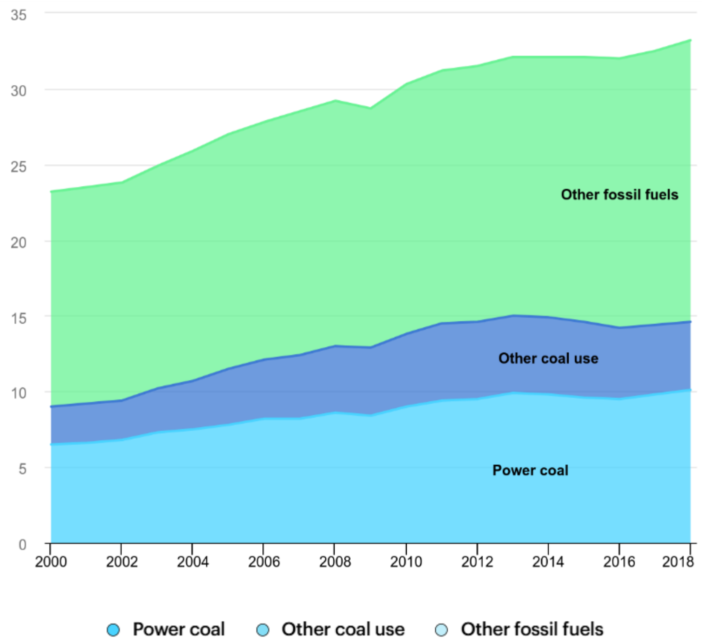

Figure 2: Global energy-related CO2 emissions by fuel, 2000-2018[11].

2.2 Refrigerants and Global Warming

Many cooling systems use hydro fluorocarbons (HFCs) as refrigerants, which are potent greenhouse gases with global warming potentials thousands of times greater than CO_2. The Kigali Amendment to the Montreal Protocol aims to phase down HFCs, but the transition to low-GWP refrigerants must be accelerated. The Space cooling average efficiency in the Sustainable Development Scenario for the period of 1990-2030 is presented in Figure 3.

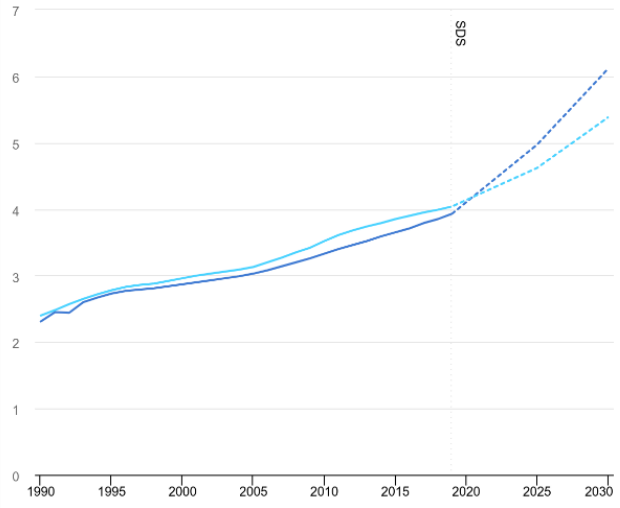

Figure 3: Space cooling average efficiency in the Sustainable Development Scenario, 1990-2030[12].

2.3 Urban Heat Islands

The widespread use of air conditioning exacerbates urban heat islands, where cities become significantly warmer than their rural surroundings due to human activities[7]. This phenomenon increases energy demand for cooling, creating a feedback loop that further strains energy systems.

3. Renewable Energy Solutions for Cooling

3.1 Solar-Powered Cooling

Solar energy is one of the most promising renewable sources for cooling applicationsas presented in Figure 4 [13]. Solar photovoltaic (PV) systems can power electric air conditioners, while solar thermal systems can drive absorption or adsorption chillers[14]. These systems are particularly effective in regions with high solar irradiance, where cooling demand aligns with solar availability[15].

Figure 4: Energy storage system or battery container unit with solar power

3.2 Wind-Powered Cooling

Wind energy can be harnessed to power electric cooling systems, especially in regions with consistent wind patterns[16], [17], [18]. Wind turbines can be integrated into microgrids to provide reliable and sustainable cooling for residential, commercial, and industrial applications as shown in Figure 5.

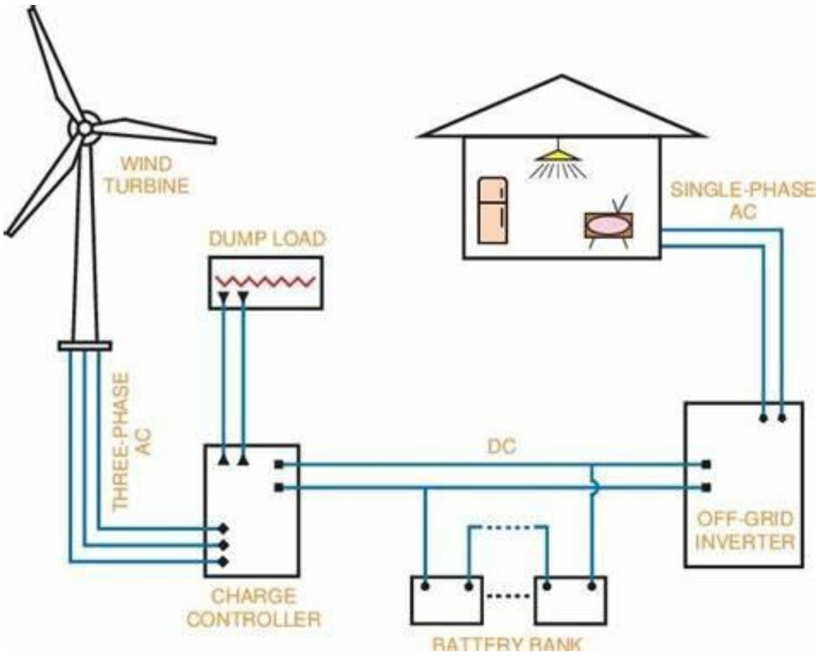

Figure 5: Wind power cooling integration for home appliances.

3.3 Geothermal Cooling

Geothermal energy offers a highly efficient solution for both heating and cooling as illustrated in Figure 6. Ground-source heat pumps use the stable temperature of the Earth to provide cooling in summer and heating in winter, reducing energy consumption by up to 50% compared to conventional systems[19], [20].

Figure 6: Geothermal cooling system operation[21].

3.4 Hydropower and Biomass

Hydropower and biomass can also contribute to sustainable cooling, particularly in regions with abundant water resources or agricultural waste[22], [23]. These sources can provide baseload power for large-scale cooling systems, ensuring reliability and resilience.

4. Technological Innovations in Sustainable Cooling

4.1 Energy-Efficient Cooling Technologies

Advancements in cooling technologies as presented in Figure 7 are critical to reducing energy demand. Inverter-based air conditioners, evaporative coolers, and thermally driven chillers are examples of energy-efficient systems that can be powered by renewables[24], [25]. These technologies not only reduce energy consumption but also improve performance and reliability.

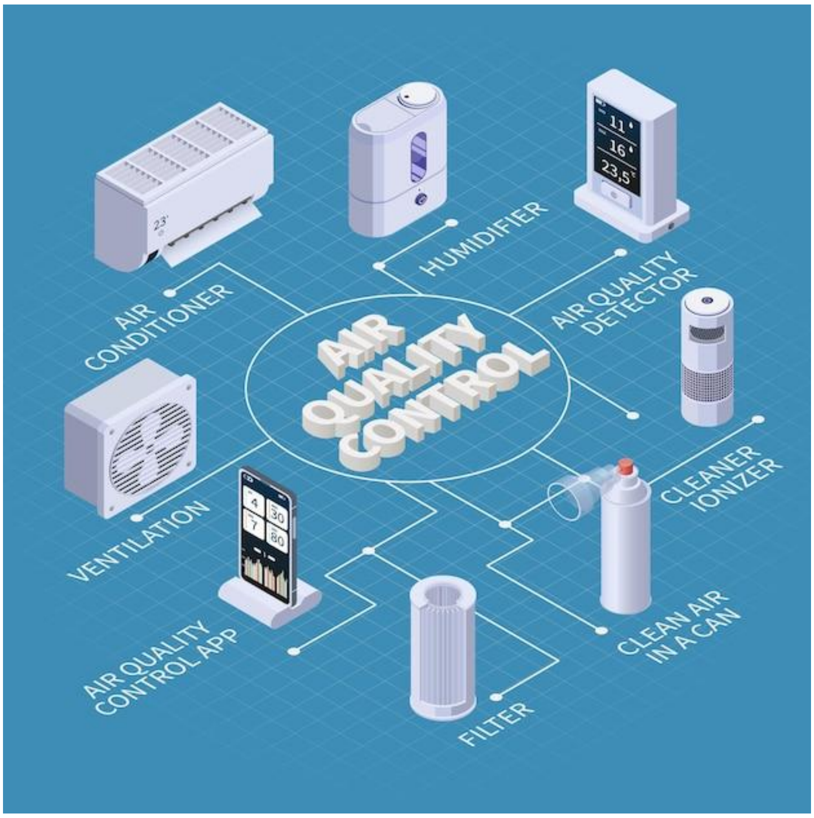

Figure 7: Air conditioning techniques.

4.2 Thermal Energy Storage

Thermal energy storage (TES) systems allow excess renewable energy to be stored as heat or cold for later use[26]. For example, ice storage systems can freeze water using solar energy during the day and use the ice for cooling at night, balancing supply and demand.

4.3 Green Refrigerants

Replacing HFCs with natural refrigerants like ammonia, carbon dioxide, or hydrocarbons can significantly reduce the climate impact of cooling systems[27]. These refrigerants have low global warming potential (GWP) and are compatible with renewable energy-powered systems. The answer of the question of why is climate change accurse is presented in Figure 8.

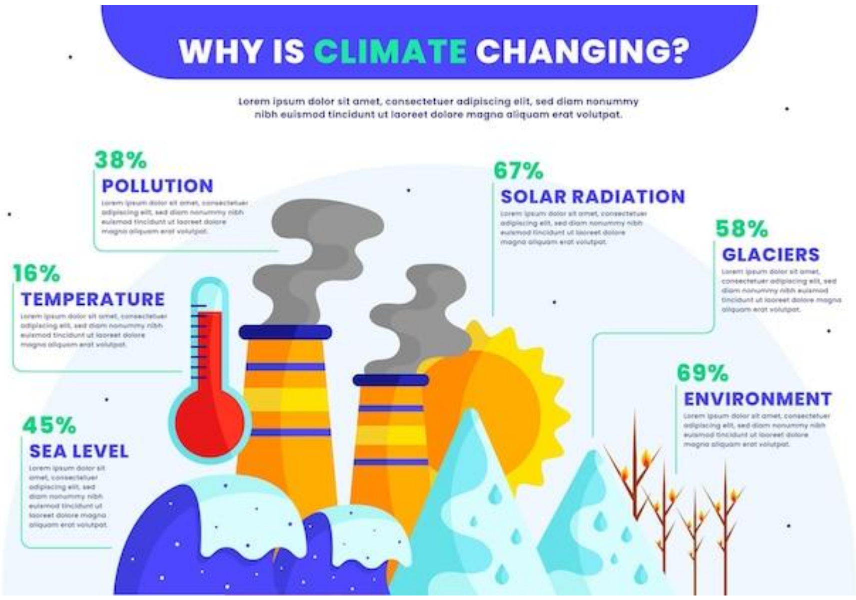

Figure 8: Why is climate change?[28].

4.4 Smart Cooling Systems

Smart technologies, such as IoT-enabled thermostats and energy management systems, can optimize cooling performance by adjusting settings based on occupancy, weather conditions, and energy availability are demonstrated in Figure 9[29]. These systems enhance energy efficiency and reduce operational costs. Smart home poster with climate control technology symbols realistic illustration.

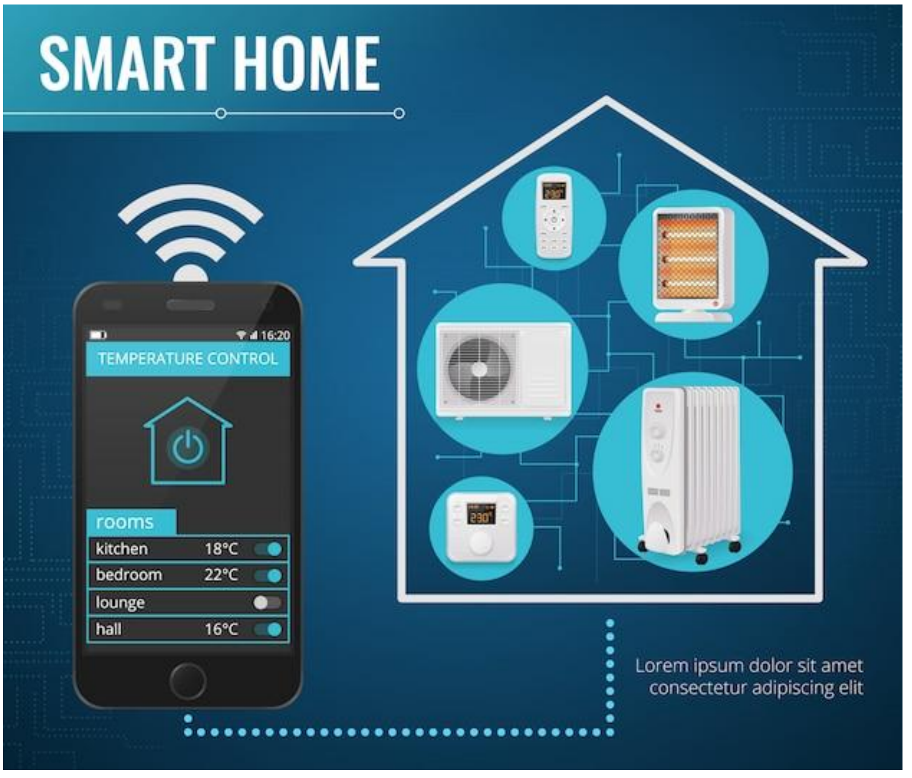

Figure 9:cooling system in smart home.

5. Policy and Economic Considerations

Table1: Policy and economic consideration.

Policy and economic consideration	**Explanation**
Government Incentives and Regulations	• Governments play a crucial role in promoting renewable-powered cooling through policies such as subsidies, tax incentives, and renewable energy mandates. • Regulations phasing out HFCs and promoting energy efficiency standards can also drive the adoption of sustainable cooling technologies.
Economic Viability	• While the upfront costs of renewable-powered cooling systems can be high, the long-term savings in energy bills and environmental benefits make them economically viable. • Falling costs of solar panels, wind turbines, and energy storage systems are further improving the business case for renewable cooling
Financing Models	• Innovative financing models, such as pay-as-you-go systems and green bonds, can make renewable cooling accessible to low-income households and developing countries. • Public-private partnerships can also mobilize investment in large-scale renewable cooling projects.

6. Case Studies and Success Stories

6.1 Solar-Powered Air Conditioning in India

India geographical map is shown in Figure 10 as one of the hottest countries in the world, has embraced solar-powered air conditioning to reduce its reliance on fossil fuels[30]. Companies like Godrej and Voltas have developed solar AC units that are being deployed in homes, offices, and hospitals.

Figure 10: Indian geographical map[31].

Based on IEA reports[32], Southeast Asia is set to be one of the world's largest engines of energy demand growth over the next decade as its rapid economic, population and manufacturing expansions drive up consumption[33].

6.2 Geothermal Cooling in Iceland

Iceland has leveraged its abundant geothermal resources to provide sustainable heating and cooling for its population. Geothermal heat pumps are widely used in residential and commercial buildings, reducing energy costs and carbon emissions as presented in Figure 11.

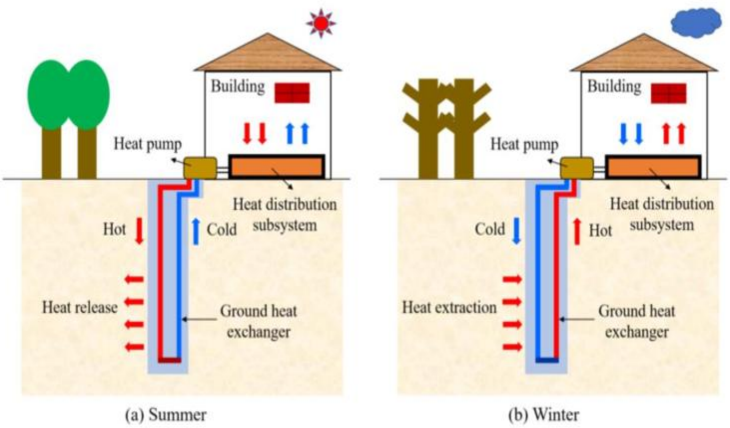

Figure11: geothermal cooling Iceland's [34].

6.3 Off-Grid Solar Cooling in Africa

In rural Africa, off-grid solar cooling systems are being used to refrigerate vaccines and preserve food, improving healthcare and food security[35], [36]. Organizations like UNICEF and the World Food Programmed are leading these initiatives[37].

7. Results and Discussion

Figure 12 is used to analyze the relationship between temperature changes and the corresponding cooling demand, which can be useful for energy management, HVAC system design, or understanding thermal comfort in a building.While Figure 13 illustrated the Cumulative cost comparison over time.This suggests that the graph also includes data on the cooling demand, which could be measured in kilowatts (kW). Cooling demand typically refers to the amount of energy required to maintain a desired indoor temperature, especially in air conditioning systems.

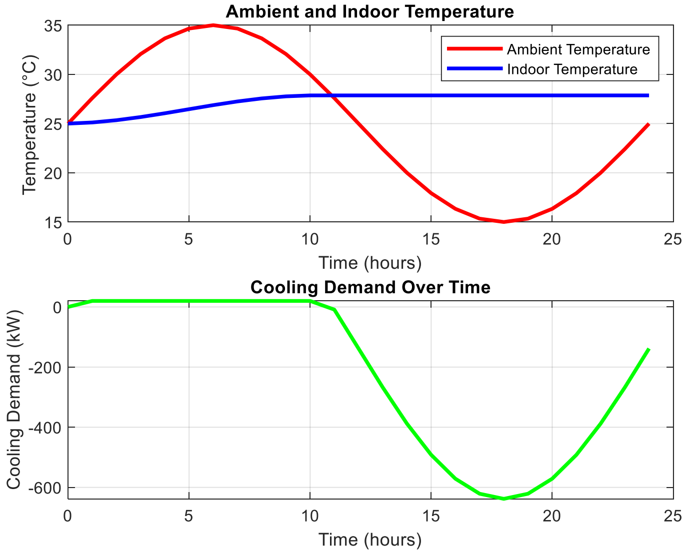

Figure 12: output results: (a) ambient and indoor temperature and (b)cooling demand over time

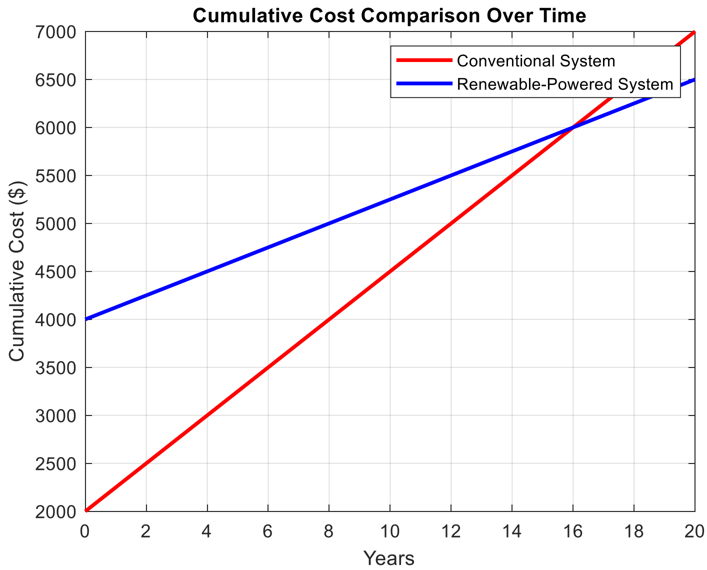

Figure13: Cumulative cost comparison over time.

Simulation ResultsRenewable-Powered Cooling for Cooling Demand is considered as 5000.00 kWh/year. The remains' obtained results are tabulated in Tables 2 – 4, respectively

Table 2: Conventional System.

Output results	Value
Energy Consumption	1666.67 kWh/year
Carbon Emissions	833.33 kg CO2/year
Annual Energy Cost	$250.00/year

Table 3: Renewable-Powered System .

Renewable Powered s	Values
Energy Consumption	1250.00 kWh/year
Carbon Emissions	0.00 kg CO2/year
Annual Energy Cost	$125.00/year

Table 4: Savings and Payback Period.

Saving and payback	Values
Annual Energy Savings	$125.00/year
Payback Period	16.00 years

8. Challenges and Future Directions

The main faced challenges and suggested future direction in order to utile the cooling techniques are tabulated in Table 5.

Table 5: Challenges and future directions**.**

Challenges and future directions	Explanation
Technical Challenges	• Integrating renewable energy with cooling systems requires overcoming technical challenges such as intermittency, energy storage, and grid integration. • Advances in smart grids, battery storage, and hybrid systems are essential to address these issues.
Awareness and Education	• Raising awareness about the benefits of renewable-powered cooling is critical to driving adoption. • Educational campaigns and training programs can equip consumers, technicians, and policymakers with the knowledge needed to embrace sustainable cooling
Research and Development	• Continued investment in research and development is needed to improve the efficiency, affordability, and scalability of renewable cooling technologies. • Collaboration between governments, academia, and industry can accelerate innovation.

Conclusion

Powering cooling with renewables is not just a technological opportunity but a moral imperative. By transitioning to sustainable cooling systems, we can mitigate climate change, improve energy access, and enhance quality of life for billions of people. The path to sustainable air conditioning and refrigeration requires a concerted effort from governments, businesses, and individuals. With the right policies, technologies, and investments, we can create a cooler, greener, and more equitable world.

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