

A state-of-the-art review of Using alternative energy to reduce air conditioning loads

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Abstract

Energy efficiency is one of the most significant technological challenges of our time. The high costs of power generation and production, coupled with rising electricity load costs, have led to a focus on promoting renewable energy sources, such as solar and wind power. The world is currently witnessing a trend towards using more efficient equipment and devices to reduce electricity loads. This necessitates reducing the use of certain alternative elements, which will be identified and developed to address these issues.

Climate change has also led to higher summer temperatures in regions with historically more stable winter temperatures, including the UK, where demand for air conditioning has historically been low. Energy system planning has therefore focused on seasonal variations in demand.

This research will specifically examine the electrical load consumption of air conditioners and the reasons for their high consumption. Furthermore, it will explore alternative energy-saving solutions that go beyond simply relying on energy-efficient air conditioning systems.

1. Introduction and Background

The rapid growth in global energy demand has become one of the most important challenges facing modern societies. Population growth, urbanization, economic development, and increasing dependence on electrical and mechanical systems have contributed significantly to the continuous increase in energy consumption. At the same time, concerns regarding climate change, greenhouse gas emissions, depletion of conventional fossil-fuel resources, and fluctuations in energy prices have accelerated the transition toward more sustainable and efficient energy systems. Consequently, improving energy efficiency and increasing the contribution of renewable energy sources have become essential components of global strategies for reducing energy consumption and environmental impacts.

Among the different sectors contributing to electricity demand, buildings represent a significant proportion of total energy consumption. Within buildings, heating, ventilation, and air-conditioning (HVAC) systems are among the major consumers of electrical energy, particularly in regions characterized by high ambient temperatures and prolonged cooling seasons. Air-conditioning systems are essential for maintaining thermal comfort and acceptable indoor environmental conditions; however, their operation can impose substantial electrical loads on buildings and national power grids. The situation becomes more critical during periods of high outdoor temperatures, when cooling demand increases rapidly and air-conditioning systems may operate simultaneously across residential, commercial, and industrial buildings.

The relationship between outdoor temperature and air-conditioning electricity consumption is particularly important because cooling demand generally increases as ambient temperature rises.

During hot periods, the simultaneous operation of large numbers of cooling systems can create significant peak electrical loads. These peak loads require additional generation and network capacity and may increase the operating costs and environmental impacts of electricity systems. Therefore, reducing the electrical demand associated with air conditioning is not only a building-level energy-efficiency issue but also an important component of wider energy-system planning.

Climate change is expected to further intensify this challenge. Increasing global temperatures and the greater frequency and duration of extreme heat events are expected to increase cooling requirements in many regions. Countries and regions that have historically experienced relatively moderate summer temperatures and consequently had limited air-conditioning penetration may also experience a growing demand for mechanical cooling. The United Kingdom provides an important example of this transition. Historically, cooling demand in the UK has been considerably lower than heating demand; however, increasing summer temperatures and more frequent heatwaves are changing building cooling requirements. This change has implications for future electricity-demand patterns and requires greater consideration of cooling loads in energy-system planning.

Conventional approaches to reducing air-conditioning energy consumption have primarily focused on improving the efficiency of cooling equipment. These approaches include the development of high-efficiency compressors, variable-speed drives, improved heat exchangers, advanced refrigerants, smart thermostats, and enhanced control systems. Although such technologies can significantly reduce the energy consumption of individual air-conditioning systems, they do not eliminate the fundamental dependence of cooling systems on electricity. Furthermore, improvements in equipment efficiency alone may not be sufficient to offset the increase in cooling demand resulting from rising temperatures and the expansion of air-conditioning use.

An alternative approach is therefore to reduce the electrical energy supplied to air-conditioning systems through the integration of renewable and alternative energy technologies. Solar energy is particularly attractive for cooling applications because solar radiation and cooling demand often occur simultaneously. Photovoltaic (PV) systems can generate electricity to operate conventional air-conditioning equipment, while solar thermal technologies can provide the thermal energy required by absorption and adsorption cooling systems. Other technologies, including wind energy, geothermal and ground-source cooling, thermal energy storage, and hybrid renewable-energy systems, can also contribute to reducing the electrical demand associated with conventional cooling.

The integration of renewable energy with air-conditioning systems can provide several potential benefits. In addition to reducing grid electricity consumption, renewable-powered cooling can reduce peak electrical demand, lower operational carbon emissions, and improve the resilience of buildings and energy systems. Thermal energy storage can further enhance this integration by shifting cooling production from periods of high electricity demand to periods when renewable energy is available or electricity prices are lower. Similarly, passive cooling techniques, improved building envelopes, shading systems, natural ventilation, and advanced building energy-management systems can reduce the cooling load before mechanical air conditioning is required.

However, the effectiveness of these approaches depends strongly on climatic conditions, building characteristics, occupancy patterns, system configuration, renewable-resource availability, and economic considerations. Therefore, no single alternative energy technology can be considered universally applicable to all cooling applications. A comprehensive assessment is required to understand the advantages and limitations of different technologies and to determine how they can be integrated into efficient and reliable cooling systems.

This review therefore focuses on the state of the art in the application of alternative and renewable energy technologies for reducing air-conditioning electrical loads. The study examines the principal causes of high air-conditioning energy consumption and evaluates technological approaches that can reduce cooling-related electricity demand beyond conventional improvements in equipment efficiency. Particular attention is given to photovoltaic-powered air conditioning, solar thermal cooling, geothermal and ground-source systems, wind-assisted systems, thermal energy storage, and hybrid renewable-energy configurations. The review also considers passive cooling and demand-side management strategies as complementary approaches.

The objective of this review is to provide a comprehensive understanding of current developments in alternative-energy-assisted cooling systems, compare their potential for reducing electrical loads, identify their principal technical and operational limitations, and highlight existing research gaps. By bringing together renewable-energy technologies, energy storage, passive cooling strategies, and intelligent energy management, the review aims to identify promising pathways toward low-carbon, resilient, and energy-efficient air-conditioning systems capable of meeting future cooling demands under changing climatic conditions.

The global use of air-conditioning systems is expected to increase significantly in the coming years, driven by rising income levels, broader access to electricity, declining costs of air-conditioning equipment, and the increasing ambient temperatures associated with climate change. Although temperate countries have historically experienced relatively low demand for residential space cooling compared with space heating, the changing climate is altering this pattern. In particular, the increasing frequency and intensity of extreme heat events are expected to contribute to a substantial growth in cooling demand in these regions.

Traditionally, annual peak electricity demand in temperate countries has occurred during the winter season, and consequently, energy-system planning has primarily focused on ensuring adequate electricity supply during periods of high winter demand. However, the projected growth in air-conditioning use may significantly modify seasonal electricity-demand patterns by increasing summer peak loads and placing additional pressure on electricity-generation and distribution infrastructure.

The growing contribution of air-conditioning to electricity consumption has therefore become an important concern for future energy systems. In this context, the International Energy Agency (IEA) has emphasized the urgent need for coordinated policies and strategies aimed at limiting the growth of energy demand associated with cooling. Addressing this challenge requires not only improvements in the efficiency of conventional air-conditioning technologies but also the integration of alternative energy sources, energy-storage technologies, passive cooling strategies, and advanced energy-management approaches to reduce both cooling-related electricity consumption and peak electrical loads.

Meeting periods of peak electricity demand can impose significant economic and operational pressures on power systems, as supplying additional generation capacity during peak periods is often associated with higher costs. Furthermore, increased peak demand may result in greater reliance on fossil-fuel-based generation, thereby increasing carbon emissions and potentially undermining decarbonization efforts. High ambient temperatures can also adversely affect the efficiency and available capacity of electricity-generation, transmission, and distribution infrastructure.

Consequently, the simultaneous occurrence of reduced system capacity and increased electricity demand during periods of extreme heat may increase the risk of load shedding, network congestion, and higher system operating costs.

However, the implications of increasing cooling demand may differ considerably among countries depending on the structure of their electricity systems. Many countries are already developing low-carbon electricity systems capable of accommodating substantially higher peak loads resulting from the increasing electrification of space heating. The additional capacity required to meet winter heating demand may therefore provide a degree of flexibility for accommodating future increases in electricity consumption associated with space cooling. Nevertheless, the extent to which rising cooling demand will affect electricity systems that have traditionally been dominated by heating demand remains insufficiently understood. Further investigation is therefore required to assess the interaction between changing seasonal demand profiles, climate-related increases in cooling requirements, electricity-system capacity, and the availability of low-carbon generation.

These issues are particularly relevant to Great Britain (GB), comprising England, Scotland, and Wales, while Northern Ireland is supplied through a separate electricity system. Climate projections indicate that summers in Great Britain are expected to become progressively warmer and drier, with heatwaves becoming more frequent and intense. This trend has already been observed, with temperatures exceeding 40 °C recorded in Great Britain for the first time in July 2022.

The potential increase in cooling demand becomes particularly significant when considered against the historically dominant requirement for space heating. Under a global warming scenario of 2 °C, the ratio of cooling degree days (CDD), representing degree days above 22 °C, to heating degree days (HDD), representing degree days below 15.5 °C, in England is projected to increase from approximately 1:85 under current conditions to 1:27. In London, this ratio is projected to reach approximately 1:13. These projections demonstrate a potentially substantial shift in the seasonal balance between heating and cooling demand and highlight the importance of incorporating future air-conditioning loads into electricity-system planning, renewable-energy integration, and long-term low-carbon energy strategies.

2. Research Methodology

2.1 Research Approach

This study adopts a systematic state-of-the-art review methodology to investigate the potential of alternative energy technologies for reducing the electrical loads associated with air-conditioning systems. The methodology combines a comprehensive review of previous research with a comparative assessment of renewable-energy-assisted cooling technologies. The analysis focuses on the energy performance of air-conditioning systems, the factors responsible for their high electricity consumption, and the potential of alternative energy sources to reduce both total energy consumption and peak electrical demand.

The methodology is organized into five main stages: (1) identification and classification of air-conditioning energy loads, (2) assessment of the factors affecting cooling energy consumption, (3) investigation of alternative and renewable energy technologies, (4) comparative evaluation of their performance, and (5) identification of research gaps and future research opportunities.

2.2 Literature Search and Selection

A structured literature search will be conducted using major scientific databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. Relevant publications will be identified using combinations of keywords such as:

- “air-conditioning energy consumption”
- “cooling load reduction”
- “renewable energy cooling”
- “solar-powered air conditioning”
- “photovoltaic air conditioning”
- “solar thermal cooling”
- “geothermal cooling”
- “thermal energy storage”
- “hybrid renewable energy cooling”
- “air-conditioning peak load”
- “climate change and cooling demand”

The review will primarily consider peer-reviewed journal articles, conference papers, technical reports, and recognized international energy-agency publications. Studies will be selected according to their relevance to air-conditioning energy consumption, alternative energy integration, cooling-load reduction, energy efficiency, or electricity-demand management.

2.3 Classification of Alternative Energy Technologies

The identified technologies will be classified according to their energy source and method of integration with the cooling system. The principal categories considered in this study are:

1. Solar photovoltaic (PV) systems integrated with conventional vapor-compression air-conditioning systems.
2. Solar thermal cooling systems, including absorption and adsorption cooling.
3. Wind-energy-assisted cooling systems.
4. Geothermal and ground-source cooling systems.
5. Thermal energy storage systems for shifting cooling demand away from peak electricity periods.
6. Hybrid renewable-energy systems, combining two or more renewable sources with conventional or storage technologies.

Passive cooling and building-level energy-efficiency measures will also be considered as complementary approaches because reducing the cooling load directly can decrease the required capacity and electricity consumption of air-conditioning systems.

2.4 Experimental or Simulation Framework

Where experimental or simulation data are available, a reference air-conditioning system will first be established as the baseline case. The baseline system will represent a conventional electrically powered air-conditioning unit operating without renewable-energy integration.

The alternative configurations will then be evaluated under equivalent operating conditions. The main parameters to be considered include:

- Outdoor air temperature.
- Indoor set-point temperature.
- Relative humidity.
- Cooling capacity.
- Electrical power consumption.
- Operating hours.
- Coefficient of performance (COP).
- Daily and annual cooling energy demand.
- Peak electrical load.
- Renewable-energy contribution.
- Energy-storage capacity, where applicable.
- Carbon emissions associated with electricity consumption.

The comparison will be conducted using identical cooling requirements and boundary conditions to ensure that differences in energy performance are attributable primarily to the alternative-energy configuration.

2.5 Climate and Sensitivity Analysis

Because cooling demand is strongly dependent on outdoor temperature, a sensitivity analysis will be performed to investigate the effect of increasing ambient temperatures on air-conditioning energy consumption. Different temperature scenarios can be considered to represent current and future climatic conditions.

The analysis will examine how changes in outdoor temperature affect:

- Cooling load.
- Daily electricity consumption.
- Annual cooling energy.
- Peak electrical demand.
- Renewable-energy contribution.
- Required system capacity.

This analysis will be particularly relevant to regions experiencing increasing summer temperatures and more frequent extreme-heat events.

2.6 Data Analysis and Research Gap Identification

The collected results will be analyzed using comparative and statistical methods where sufficient quantitative data are available. Reported energy savings, peak-load reductions, renewable-energy fractions, and other performance indicators will be compared across the selected technologies.

Finally, the reviewed studies will be analyzed to identify limitations and research gaps related to system integration, climatic applicability, economic feasibility, energy storage, reliability, and scalability. Particular attention will be given to the limited understanding of how increasing cooling demand interacts with low-carbon electricity systems and how alternative energy technologies can reduce both total electricity consumption and peak air-conditioning loads.

The methodology therefore provides a structured framework for evaluating alternative energy technologies and identifying the most promising approaches for reducing air-conditioning electricity consumption while supporting the transition toward low-carbon and resilient energy systems.

3. Results

3.1 Overview of the Review Findings

The reviewed literature demonstrates that air-conditioning systems represent a significant source of electricity consumption, particularly during periods of high ambient temperature. The increase in cooling demand associated with climate change, urbanization, and the wider adoption of mechanical cooling is expected to increase both annual electricity consumption and peak electrical loads. The findings indicate that improving the efficiency of conventional air-conditioning equipment alone may not be sufficient to address the projected increase in cooling demand.

The literature reviewed in this study indicates that the integration of renewable energy sources, thermal energy storage, passive cooling techniques, and intelligent energy-management strategies can provide additional opportunities for reducing air-conditioning electricity consumption. Among the technologies investigated, solar photovoltaic systems, solar thermal cooling, geothermal cooling, and thermal energy storage received considerable attention because of their potential to reduce dependence on conventional grid electricity.

3.2 Factors Affecting Air-Conditioning Energy Consumption

The analysis identified several major factors influencing the electrical consumption of air-conditioning systems. Outdoor air temperature was found to be one of the most important factors because increasing ambient temperature increases the cooling load and consequently the operating time and power consumption of the air-conditioning system.

Other important factors include indoor temperature set-point, building thermal characteristics, solar heat gains, occupancy, equipment efficiency, relative humidity, ventilation requirements, and operating schedules. Poor building-envelope performance can significantly increase cooling loads by allowing greater heat transfer through walls, roofs, windows, and other building components.

The reviewed studies also indicate that air-conditioning electricity demand is highly sensitive to extreme-weather conditions. During heatwave events, cooling systems may operate continuously or near their rated capacity, resulting in substantial increases in peak electricity demand. This finding emphasizes the importance of addressing both total energy consumption and peak cooling loads.

3.3 Effectiveness of Renewable Energy Integration

The results indicate that renewable-energy integration can substantially reduce the amount of electricity supplied to air-conditioning systems from the conventional electrical grid. Solar energy was identified as particularly suitable for cooling applications because solar availability generally coincides with periods of high cooling demand.

3.3.1 Photovoltaic-Powered Air Conditioning

Photovoltaic (PV) systems were identified as one of the most promising approaches for reducing the grid electricity consumption of conventional vapor-compression air-conditioning systems. During

periods of strong solar radiation, PV generation can directly supply part or all of the electrical demand of the cooling system.

The effectiveness of PV-assisted cooling depends on the installed PV capacity, solar radiation, system efficiency, cooling demand, and operating schedule. The greatest benefit occurs when the air-conditioning load coincides with periods of high solar-energy production. However, the mismatch between solar availability and cooling demand during evening or nighttime periods may require battery storage or grid interaction.

The reviewed literature therefore indicates that PV-assisted air conditioning can reduce grid dependence while simultaneously contributing to peak-load reduction, particularly in regions characterized by high solar resources and strong daytime cooling demand.

3.4 Solar Thermal Cooling

Solar thermal cooling systems provide another approach for utilizing renewable energy for air-conditioning applications. These systems convert solar thermal energy into useful cooling through thermally driven technologies such as absorption and adsorption chillers.

The main advantage of solar thermal cooling is that it can utilize solar heat directly rather than converting solar energy into electricity first. This approach can reduce electrical consumption associated with conventional vapor-compression systems. However, the performance of solar thermal cooling systems depends strongly on solar radiation, collector efficiency, thermal storage, cooling-water temperature, and system operating conditions.

The reviewed studies indicate that solar thermal cooling is particularly suitable for buildings with substantial daytime cooling requirements and sufficient solar resources. Nevertheless, higher initial costs, system complexity, and the need for appropriate thermal storage and backup systems remain important challenges.

3.5 Geothermal and Ground-Source Cooling

Ground-source and geothermal cooling technologies were found to provide an alternative method for reducing cooling-system electricity consumption by utilizing the relatively stable temperature of the ground as a heat sink. Compared with conventional air-source systems, ground-source heat pumps can operate under more favorable temperature conditions, potentially improving system efficiency.

The results indicate that geothermal systems can provide stable cooling performance over a wide range of outdoor temperatures. Their main limitations include high initial installation costs, site-specific geological conditions, drilling requirements, and the availability of sufficient ground area for heat-exchange systems.

Consequently, geothermal cooling appears particularly suitable for new buildings and locations where the required ground conditions and installation infrastructure are available.

3.6 Thermal Energy Storage

Thermal energy storage was identified as an important technology for reducing peak electrical demand associated with air conditioning. Rather than relying exclusively on real-time cooling production, thermal storage allows cooling energy to be produced and stored during periods of low electricity demand or high renewable-energy availability.

During peak-demand periods, stored cooling energy can be used to reduce the operating load of mechanical cooling equipment. This approach can therefore provide two major benefits: reducing peak electricity demand and improving the utilization of renewable energy.

The effectiveness of thermal storage depends on storage capacity, charging and discharging efficiency, thermal losses, control strategy, and the daily cooling-load profile. The literature indicates that combining thermal storage with photovoltaic generation can be particularly beneficial because excess daytime solar electricity can be used to produce and store cooling for later use.

3.7 Hybrid Renewable-Energy Systems

The review demonstrates that hybrid systems combining multiple technologies can overcome some of the limitations associated with individual renewable-energy technologies. Examples include PV combined with battery storage, PV combined with thermal energy storage, solar thermal systems with auxiliary conventional cooling, and hybrid solar-geothermal systems.

Hybrid configurations provide greater operational flexibility and can improve the reliability of renewable-powered cooling. They can also reduce the mismatch between renewable-energy availability and cooling demand. However, increasing system complexity can result in higher initial costs and greater requirements for control, monitoring, and maintenance.

The findings therefore suggest that system optimization and appropriate energy-management strategies are essential for achieving the maximum benefit from hybrid configurations.

3.8 Passive Cooling and Demand-Side Strategies

The reviewed literature indicates that reducing the cooling load before applying renewable-energy technologies can significantly improve the overall performance of an air-conditioning system. Passive strategies include improved building insulation, reflective roofs, external shading, high-performance glazing, natural ventilation, and reduction of unwanted solar heat gains.

These measures reduce the amount of heat entering the building and consequently decrease the required cooling capacity. Unlike renewable-energy systems, passive measures generally reduce energy demand at the source and can therefore provide long-term reductions in both cooling energy consumption and peak electrical load.

The results indicate that combining passive cooling measures with renewable-energy technologies is more effective than considering either approach independently. Reducing the cooling load decreases the size of the required air-conditioning and renewable-energy systems, potentially reducing capital and operating costs.

3.9 Impact on Peak Electricity Demand

One of the most significant findings is that alternative-energy technologies can contribute not only to reducing annual electricity consumption but also to reducing peak electrical demand. This distinction is important because peak demand determines the required capacity of electricity-generation, transmission, and distribution infrastructure.

PV systems can reduce daytime peak demand when solar generation coincides with cooling loads. Thermal energy storage can provide additional peak reduction by shifting cooling production to

periods of lower demand. Passive cooling measures reduce the magnitude of the cooling load itself and therefore provide a direct reduction in peak air-conditioning power requirements.

The combination of these approaches can potentially provide greater peak-load reduction than the implementation of energy-efficient air-conditioning equipment alone.

3.10 Impact of Climate Change on Cooling Demand

The reviewed literature confirms that increasing ambient temperatures are expected to increase cooling requirements and modify seasonal electricity-demand patterns. Regions that have historically been dominated by heating demand may experience a growing contribution from cooling loads as summer temperatures increase.

This finding is particularly relevant to temperate regions such as Great Britain, where historically low residential cooling demand has resulted in electricity-system planning being strongly influenced by winter heating requirements. Increasing summer temperatures and more frequent heatwave events may lead to a growing requirement for cooling capacity and greater summer peak electricity demand.

The results therefore demonstrate the importance of incorporating future cooling demand into long-term electricity-system planning and renewable-energy strategies.

3.11 Overall Research Findings

The overall results of the state-of-the-art review demonstrate that reducing air-conditioning electricity consumption requires a combination of measures rather than dependence on a single technology. Improving the efficiency of conventional cooling equipment remains important, but renewable-energy integration, thermal energy storage, passive cooling, and intelligent energy management can provide additional and complementary reductions.

Among the reviewed technologies, photovoltaic-powered air conditioning and thermal energy storage show strong potential for reducing grid electricity consumption and peak cooling loads, particularly when properly matched to the building cooling profile. Solar thermal and geothermal cooling provide additional opportunities in locations with appropriate solar and geological conditions. Hybrid systems offer increased flexibility and reliability but require more sophisticated design and control.

The findings also reveal an important research gap concerning the integration of alternative-energy cooling technologies with future electricity systems under changing climatic conditions. Further research is required to optimize system sizing, renewable-energy utilization, thermal storage, control strategies, economic performance, and long-term operation under different climate scenarios.

Overall, the review supports the development of integrated cooling systems in which energy efficiency, renewable energy, passive cooling, and energy storage are considered simultaneously. Such an integrated approach can contribute to reducing air-conditioning electricity consumption, limiting peak electrical demand, lowering carbon emissions, and improving the resilience of future low-carbon energy systems.

4. Conclusions:

- Air-conditioning systems represent a significant and growing contributor to electricity consumption and peak electrical demand, particularly during periods of high ambient temperature.
- Climate change is expected to increase cooling requirements through rising average temperatures and more frequent and intense heatwave events, placing additional pressure on electricity-generation, transmission, and distribution infrastructure.
- Improving the efficiency of conventional air-conditioning equipment is important but may not be sufficient to offset the projected growth in cooling demand.
- Renewable-energy technologies provide an effective pathway for reducing the dependence of air-conditioning systems on conventional grid electricity.
- Solar photovoltaic (PV) systems have considerable potential for supplying the electrical demand of air-conditioning systems, particularly in regions with high solar radiation and significant daytime cooling loads.
- Solar thermal cooling can reduce electrical consumption by using solar thermal energy to drive absorption or adsorption cooling systems, although system complexity and initial costs remain important challenges.
- Geothermal and ground-source cooling systems can provide efficient and relatively stable cooling performance, but their application depends on site characteristics and installation costs.
- Thermal energy storage can significantly contribute to reducing peak electrical demand by shifting cooling production from high-demand periods to periods of lower electricity demand or higher renewable-energy availability.
- Hybrid renewable-energy systems can improve reliability and flexibility by combining complementary technologies such as photovoltaic generation, energy storage, and conventional cooling systems.
- Passive cooling measures, including improved insulation, solar shading, reflective surfaces, high-performance glazing, and natural ventilation, can reduce the cooling load before mechanical air conditioning is required.
- The integration of renewable energy, energy storage, passive cooling, and intelligent energy management can provide greater benefits than relying solely on improvements in air-conditioning equipment efficiency.
- The most appropriate alternative-energy technology depends on climatic conditions, building characteristics, cooling-load profiles, renewable-resource availability, economic factors, and system requirements.
- Future electricity-system planning should explicitly consider the potential growth of cooling demand, particularly in regions where electricity systems have historically been dominated by space-heating requirements.
- Further research is required to optimize system sizing, renewable-energy utilization, thermal-storage capacity, control strategies, economic performance, and system operation under future climate scenarios.
- Overall, the integration of alternative energy technologies with efficient cooling strategies represents a promising pathway toward lower electricity consumption, reduced peak loads, lower carbon emissions, and more resilient low-carbon cooling systems.

References

1. International Energy Agency (IEA), *The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning*, Paris, France: IEA, 2018.
2. IPCC, “Chapter 9: Buildings,” in *Climate Change 2022: Mitigation of Climate Change*, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2022.
3. IPCC, “Chapter 12: Climate Change Information for Regional Impact and for Risk Assessment,” in *Climate Change 2021: The Physical Science Basis*, Working Group I contribution to the Sixth Assessment Report, Cambridge University Press, 2021.
4. I. Sarbu and C. Sebarchievici, “General review of ground-source heat pump systems for heating and cooling of buildings,” *Energy and Buildings*, vol. 70, pp. 441–454, 2014, doi: 10.1016/j.enbuild.2013.11.068.
5. M. H. Ahmadi, M. A. Ahmadi, M. S. Sadaghiani, M. Ghazvini, S. Shahriar, and M. Alhuyi Nazari, “Ground source heat pump carbon emissions and ground-source heat pump systems for heating and cooling of buildings: A review,” *Environmental Progress & Sustainable Energy*, vol. 37, no. 4, pp. 1241–1265, 2018, doi: 10.1002/ep.12802.
6. “A review on solar-powered cooling and air-conditioning systems for building applications,” *Energy Reports*, vol. 8, pp. 2888–2907, 2022, doi: 10.1016/j.egyr.2022.01.172.
7. A. A. Al-Abidi, S. Mat, K. Sopian, M. Y. Sulaiman, and C. H. Lim, “Review of thermal energy storage for air conditioning systems,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 5802–5819, 2012.
8. A. T. Muzhanje, M. A. Hassan, and H. Hassan, “Phase change material based thermal energy storage applications for air conditioning: Review,” *Applied Thermal Engineering*, 2022, doi: 10.1016/j.applthermaleng.2022.118832.
9. N. A. Hussein, A. M. Al Jubori, and A. S. Abdul-Zahra, “Enhancing the performance of air conditioning systems by integrating phase change materials: A comprehensive review,” *Journal of Energy Storage*, vol. 101, 2024, Art. no. 113857.
10. P. Adebayo, C. B. Jathunge, A. Darbandi, N. Fry, R. Shor, A. Mohamad, C. Wemhöner, and A. Mwesigye, “Development, modeling, and optimization of ground source heat pump systems for cold climates: A comprehensive review,” *Energy and Buildings*, vol. 320, 2024, Art. no. 114646.
11. International Energy Agency (IEA), “Air conditioning use emerges as one of the key drivers of global electricity-demand growth,” IEA, Paris, France, 2018.
12. Met Office, “A milestone in UK climate history,” UK Met Office, July 2022. The report documents the first UK temperature exceeding 40°C, with 40.3°C recorded at Coningsby on 19 July 2022.
13. Met Office, “Record breaking 2022 indicative of future UK climate,” UK Met Office, 2023.
14. IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability*, Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2022.
15. IPCC, *Climate Change 2022: Mitigation of Climate Change*, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2022.
16. R. Khosla, O. Abdelaziz, R. Gluckman, L. Riahi, S. Bhasin, *Keeping It Chill*, UN Environment Program, 2023, <https://doi.org/10.59117/20.500.11822/44243>.
17. R.A. Betts, K. Brown, F. Fung, J.A. Lowe, et al., <https://www.ukclimaterisk.org/independent-assessment-ccra3/technical-report/>, 2021. (Accessed 4 September 2023).

18. B. Dean, J. Dulac, T. Morgan, U. Remme, The future of cooling, International Energy Agency (IEA), 2018. https://iea.blob.core.windows.net/assets/0bb_45525-277f-4c9c-8d0c-9c0cb5e7d525/The_Future_of_Cooling.pdf. (Accessed 12 December 2024).
19. M. Auffhammer, P. Baylis, C.H. Hausman, Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States, *Proc. Natl. Acad. Sci.* 114 (8) (2017) 1886–1891, <https://doi.org/10.1073/pnas.1613193114>.
20. O. Jay, A. Capon, P. Berry, et al., Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities, *Lancet* 398 (10301) (2021) 709–724, [https://doi.org/10.1016/S0140-6736\(21\)01209-5](https://doi.org/10.1016/S0140-6736(21)01209-5).
21. C. McGuire, Y. Naderi, A. Gardner, et al., Impacts on energy assets from extreme heat and heatwaves. <https://www.gov.uk/government/publications/impacts-on-energy-assets-from-extreme-heat-and-heatwaves>, 2025. (Accessed 23 June 2025).
22. CAISO, CPUC, CEC, Root cause analysis: mid-August 2020 extreme heat wave. <https://web.archive.org/web/20251220070812/https://www.cpuc.ca.gov/news-and-updates/all-news/caiso-cpuc-cec-issue-final-report-on-causes-of-august-2020-rotating-outages>, 2021. (Accessed 6 February 2026).
23. J.A. Lowe, D. Bernie, P. Bett, et al., UKCP18 science overview report, Met Office Hadley Centre, 2018. <https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf>. (Accessed 12 June 2023).
24. M. Kendon, M. McCarthy, S. Jevrejeva, et al., State of the UK climate 2022, *Int. J. Climatol.* 43 (S1) (2023) 1–83, <https://doi.org/10.1002/joc.8167>.
25. N.W. Arnell, A. Freeman, A.L. Kay, A.C. Rudd, J.A. Lowe, Indicators of climate risk in the UK at different levels of warming, *Environ. Res. Commun.* 3 (9) (2021) 095005, <https://doi.org/10.1088/2515-7620/ac24c0>.
26. National Energy System Operator (NESO), Response to heat resilience & sustainable cooling inquiry by the Environmental Audit Committee. <https://committees.parliament.uk/writtenevidence/125760/pdf/>, 2023. (Accessed 11 December 2024).
27. National Energy System Operator, Future energy scenarios: ESO pathways to Net Zero. <https://www.neso.energy/document/321041/download>, 2024. (Accessed 6 November 2024).
28. BEIS, Cooling in the UK, HM Government, 2021. <https://assets.publishing.service.gov.uk/media/614c1c75e90e077a34ed9fb7/cooling-in-uk.pdf>. (Accessed 10 December 2024).
29. J.F. Mercure, S. Sharpe, J.E. Vinuales, et al., Risk-opportunity analysis for transformative policy design and appraisal, *Glob. Environ. Chang.* 70 (2021) 102359, <https://doi.org/10.1016/j.gloenvcha.2021.102359>.
30. F. Creutzig, J. Roy, W.F. Lamb, et al., Towards demand-side solutions for mitigating climate change, *Nat. Clim. Chang.* 8 (4) (2018) 260–263, <https://doi.org/10.1038/s41558-018-0121-1>.
31. R. Hoggett, L. King, R. Lowes, C. Demski, C.E. Ugalde-Loo, People centric policy is needed to create a clean cooling pathway for UK homes, *Environ. Sci. Pol.* 167 (2025) 104045, <https://doi.org/10.1016/j.envsci.2025.104045>.
32. F. Khosravi, R. Lowes, C.E. Ugalde-Loo, Cooling is hotting up in the UK, *Energy Policy* 174 (2023) 113456, <https://doi.org/10.1016/j.enpol.2023.113456>.
33. Ministry of Housing, Communities and Local Government (MHCLG), Department for Levelling Up, Housing and Communities (DLHC), Building Regulations approved document O. <https://www.gov.uk/government/publications/overheating-approved-document-o>, 2022. (Accessed 17 February 2025).
34. Department for Energy Security and Net Zero (DESNZ), Supplementary written evidence from the Department for Energy Security and Net Zero. <https://committees.parliament.uk/writtenevidence/127172/html/>, December 19, 2023. (Accessed 14 April 2025).

35. Department for Energy Security and Net Zero (DESNZ), Clean Power 2030 Action Plan: a new era of clean electricity – main report, GOV.UK, December 18, 2024. <https://www.gov.uk/government/publications/clean-power-2030-action-plan/clean-power-2030-action-plan-a-new-era-of-clean-electricity-main-report>. (Accessed 11 April 2025).
36. Climate Change Committee, The seventh carbon budget. <https://www.theccc.org.uk/publication/the-seventh-carbon-budget/>, 2025. (Accessed 15 July 2025).
37. National Energy System Operator, Advice on achieving clean power for Great Britain by 2030. <https://www.neso.energy/document/346651/download>, 2024. (Accessed 11 April 2025).
38. J. Rosenow, N. Eyre, Reinventing energy efficiency for net zero, Energy Res. Soc. Sci. 90 (2022) 102602, <https://doi.org/10.1016/j.erss.2022.102602>.
39. Department for Levelling Up, Housing and Communities, English housing survey 2021 to 2022: Energy, GOV.UK, 2023. <https://www.gov.uk/government/statistics/english-housing-survey-2021-to-2022-energy>. (Accessed 12 September 2025).
40. Impact Research Ltd, Electricity North West (ENWL), Project CoolDown WP4 customer engagement research. <https://www.enwl.co.uk/globalassets/innovation/strategic-innovation-fund/cooldown/cooldown-alpha/wp4-customer-insight.pdf>, 2025. (Accessed 9 May 2025).
41. Department for Energy Security and Net Zero, Energy Follow Up Survey (EFUS) 2017 lights, appliances and smart technologies report. <https://www.gov.uk/government/publications/energy-follow-up-survey-efus-2017-reports>, 2021. (Accessed 5 June 2025).
42. StatBel, et al.. <https://statbel.fgov.be/fr/themes/menages/budget-des-menages/plus>, 2022. (Accessed 25 June 2025).
43. D.J. Sailor, A.A. Pavlova, Air conditioning market saturation and long-term response of residential cooling energy demand to climate change, Energy 28 (9) (2003) 941–951, [https://doi.org/10.1016/S0360-5442\(03\)00033-1](https://doi.org/10.1016/S0360-5442(03)00033-1).
44. M. Jakubcionis, J. Carlsson, Estimation of European Union residential sector space cooling potential, Energy Policy 101 (2017) 225–235, <https://doi.org/10.1016/j.enpol.2016.11.047>.
45. Climate Change Committee, Delivering a reliable decarbonised power system, Climate Change Committee, 2023. <https://www.theccc.org.uk/publication/delivering-a-reliable-decarbonised-power-system/>. (Accessed 5 April 2024).
46. Energy Systems Catapult, Domestic heat demand study, Published online, <https://es.catapult.org.uk/report/domestic-heat-demand-study/>, July 2020. (Accessed 14 June 2024).
47. A. Kingsborough, K. Jenkins, J.W. Hall, Development and appraisal of long-term adaptation pathways for managing heat-risk in London, Clim. Risk Manag. 16 (2017) 73–92, <https://doi.org/10.1016/j.crm.2017.01.001>.
48. C. McLachlan, S. Glynn, F. Hill, R. Edwards, J. Kuriakose, R. Wood, Air conditioning demand assessment, Tyndall Centre, 2016. <https://www.enwl.co.uk/globalassets/innovation/enwl001-demand-scenarios-atlas/enwl001-closedown-report/appendix-3—tyndall-uom—air-conditioningdemand-report-may2016.pdf>.
49. Statistics Austria, Mikrozensus Energieeinsatz Der Haushalte. <https://www.statistik.at/fileadmin/pages/100/10RenovationsAndAirConditions20182024.ods>, 2021.