

Review Article

Thermal Systems for Green Technologies: Sustainable Heating, Cooling, and Energy Conversion in the Circular Economy

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A B S T R A C T

The growing demand for sustainable energy solutions, together with the rising challenges posed by climate change and the steady depletion of natural resources, makes it essential to adopt thermal systems that support the principles of a circular economy. This article explores how a range of advanced thermal technologies, including heat pumps, waste heat recovery systems, thermal energy storage (TES), and waste to energy processes, can deliver efficient heating, cooling, and electricity generation while also reducing greenhouse gas emissions and limiting unnecessary resource use. We provide a detailed review of recent progress in system design, technological innovation, and methods for integrating these solutions into modern energy networks. The discussion also covers practical applications across residential, industrial, and urban settings, along with an examination of the key benefits and the challenges that may arise during implementation. In addition, a conceptual framework is presented to illustrate how thermal systems can be effectively deployed within circular economy models. Our analysis shows that combining these technologies in a well planned and coordinated manner can significantly reduce overall energy consumption, improve environmental performance, lower emissions, and promote the creation of sustainable and resource efficient energy infrastructure. This integrated approach can play an important role in supporting long term energy security and environmentally responsible development.

Keywords: Circular economy, waste heat recovery, heat pumps, thermal energy storage, waste-to-energy, sustainable heating, cooling, energy conversion, low-carbon buildings, renewable energy integration

Introduction

The rapid expansion of global urbanisation and industrialisation has resulted in a sharp rise in energy demand across all sectors, particularly for heating, cooling, and electricity generation. As populations grow and cities continue to develop, the pressure on existing energy systems becomes increasingly evident. Traditional energy infrastructures,

which depend largely on fossil fuels, are now widely considered unsustainable due to their considerable impact on the environment, their contribution to the depletion of natural resources, and their central role in increasing greenhouse gas emissions. These challenges have intensified global interest in more efficient, cleaner, and resource conscious alternatives. Within this broader shift, the circular economy

paradigm has emerged as a compelling framework for rethinking how energy systems are designed, operated, and integrated into society. This approach emphasises the efficient use of resources, the minimisation of waste, and the creation of systems in which materials and energy continually circulate rather than being discarded.

Thermal systems have become particularly important in advancing this transition, as they offer multiple pathways for improving the performance, sustainability, and resilience of energy networks. They enable the recovery and use of waste heat from industrial, commercial, and domestic processes; they support the integration of renewable energy sources such as solar thermal and geothermal energy; they allow surplus energy to be stored in the form of heat for later use; and they provide methods for converting different types of waste into useful thermal or electrical energy. These capabilities not only improve overall energy efficiency but also change the way resources are valued and managed. By treating waste streams as potential energy inputs, thermal technologies help shift industries and urban systems toward circular and regenerative models of development. This transformation strengthens long term energy security, reduces dependence on non renewable resources, and supports more sustainable patterns of growth.

This article offers an in depth examination of the essential role played by advanced thermal technologies in building energy systems that align with circular economy principles. The discussion covers a wide range of technologies, including heat pumps, thermal energy storage systems, waste heat recovery mechanisms, and waste to energy conversion methods. We begin by presenting a thorough review of recent literature that highlights the latest innovations, research trends, and technological advancements in the field. This is followed by a detailed exploration of strategies for integrating these technologies into both existing energy infrastructures and newly designed systems. We assess the core benefits they provide, such as improved efficiency, reduced emissions, cost savings, and increased system resilience, while also addressing the technical, economic, and policy challenges that may hinder widespread implementation.

In the final sections, the article presents key conclusions and outlines recommendations for future research directions, technological development, and supportive policy measures that can facilitate broader adoption. These include the need for improved system integration techniques, enhanced storage materials, better utilisation of industrial waste heat, and regulatory frameworks that encourage circular economy practices within the energy sector.

By adopting a fully integrated and holistic approach, advanced thermal systems have the potential to make substantial contributions to reducing primary energy consump-

tion, easing environmental pressures, and supporting the long-term development of sustainable, resource efficient urban and industrial ecosystems. Their successful deployment will play a crucial role in shaping the low carbon energy systems of the future.

Literature Review

Waste-Heat Recovery And Energy Recovery From Thermal Processes

A considerable portion of the world's primary energy supply is lost in the form of unused thermal waste. According to a detailed review by Xue and colleagues (2022), an estimated 63 per cent of the primary energy consumed globally is ultimately wasted during combustion, conversion, and heat transfer processes, and a significant share of this wasted heat has the potential to be recovered and reused.¹

A variety of technologies have been developed to capture and utilise this lost energy. Heat exchangers, absorption and adsorption based cooling systems, and advanced thermodynamic cycles such as the Organic Rankine Cycle (ORC) are among the most widely explored solutions for converting waste heat into useful heating, cooling, or electrical power.² These technologies demonstrate strong technical promise and have been successfully applied in industrial, commercial, and power generation settings.

Despite the substantial potential for waste heat recovery, studies consistently show that actual adoption rates remain far below what is technologically feasible. Limited deployment is often linked to several persistent constraints, including challenges in matching heat supply with demand, high initial investment costs, low energy prices in some regions, and regulatory or policy frameworks that do not adequately incentivise recovery technologies. These barriers highlight the need for coordinated policy support, improved system design, and stronger industry participation to unlock the full benefits of waste heat utilisation.³

Heat Pumps And Thermal Energy Storage (Tees) For Buildings

Heat pumps have become one of the most important technologies for reducing carbon emissions associated with heating and cooling in residential, commercial, and industrial buildings. As highlighted by Yan and colleagues (2024), modern heat pump systems are capable of operating in both heating and cooling modes, which makes them highly versatile and suitable for use throughout different seasons and across a wide range of climatic conditions.⁴ Their ability to move heat rather than generate it directly allows them to achieve significantly higher efficiency than conventional fossil fuel based heating systems.

The performance and flexibility of heat pump systems can be greatly improved when they are integrated with thermal

energy storage (TES). TES technologies include sensible heat storage and latent heat storage, the latter often using phase change materials that are able to store large amounts of energy within a small volume. These storage options enable heat pumps to shift loads, manage peak demand more effectively, and operate more efficiently by taking advantage of off peak energy availability.⁵ Such system combinations help stabilise energy consumption and reduce stress on electrical grids during periods of high demand.

Ground source heat pumps (GSHPs), especially when paired with TES, have shown particularly strong advantages. By utilising the relatively stable temperatures beneath the earth's surface, GSHPs maintain high efficiency throughout the year and offer more reliable performance than many conventional heating, ventilation, and air conditioning systems. Their widespread adoption can substantially reduce dependence on fossil fuel based heating solutions, contributing significantly to long term decarbonisation goals.⁶

In addition to these technologies, Earth to Air Heat Exchangers (EAHEs) are receiving increasing attention as passive solutions for reducing heating and cooling loads in buildings. Reviews of EAHE systems show that they can significantly cut energy requirements by pre heating or pre cooling incoming air using stable underground temperatures. Their environmental impact is minimal, and when these systems are combined with renewable energy sources, they form an effective strategy for improving building energy efficiency and lowering operational carbon emissions.⁷

Waste-to-Energy (WtE) and Thermochemical Conversion of Waste

The waste to energy approach, which involves converting municipal, industrial, and agricultural waste into useful heat, electricity, or fuel, is increasingly recognised as an essential component of circular economy strategies.⁸ By transforming waste materials that would otherwise end up in landfills or open dumping sites, waste to energy systems help reduce environmental pollution while simultaneously contributing to energy generation and resource recovery. This dual benefit makes the pathway particularly valuable for countries and cities seeking both sustainable waste management and low carbon energy solutions.

Recent technological developments have significantly enhanced the performance of waste to energy processes. Advanced thermochemical conversion methods, including pyrolysis and gasification, now enable more efficient and cleaner conversion of waste into energy rich gases, oils, and solid residues.⁹ The use of refuse derived fuel (RDF), produced by processing mixed waste into a uniform fuel, has further contributed to improved combustion stability,

higher energy yields, and better overall system efficiency. These innovations have made modern waste to energy facilities far more flexible and capable of handling diverse waste streams compared with earlier technologies.

However, despite these advancements, several challenges continue to limit large scale deployment. Maintaining strict control over emissions remains a major concern, as waste composition can vary significantly and affect combustion quality. Variability in fuel properties, especially in RDF, can lead to fluctuations in energy output and operational inconsistency. In addition, some technologies, while promising, are still in early stages of development and require further testing and optimisation before they can be widely adopted. Regulatory frameworks also need to evolve to support investment, ensure environmental compliance, and promote integration of waste to energy systems within broader waste management and energy planning strategies.⁹

Thermal Systems In The Context Of Circular Economy And Energy Transition

The convergence of thermal energy systems and circular economy principles has attracted increasing academic interest, particularly regarding the ways in which sustainable thermal infrastructures can enhance resource efficiency, minimise waste generation, and support long term decarbonisation goals. Recent studies highlight that rethinking thermal power production through the lens of the circular economy encourages the adoption of eco innovative practices and promotes cleaner, more efficient pathways for generating energy. For example, a recent review focusing on the role of thermal power plants within energy transition frameworks points out that circular economy oriented strategies can significantly improve resource use, broaden energy recovery options, and reduce environmental impacts associated with traditional power generation.¹⁰

New and emerging system configurations are also being explored to further advance this transition. These include integrated arrangements that combine renewable heat sources such as solar thermal or geothermal energy with recovered waste heat, waste to energy inputs, and various forms of thermal energy storage. When applied together, these components can support tri generation systems that produce heating, cooling, and electricity simultaneously, enabling more efficient utilisation of available resources and reducing overall energy losses.¹¹ Such configurations demonstrate strong potential for creating flexible, resilient, and low carbon energy networks suitable for both urban and industrial environments.

In summary, the existing body of literature consistently highlights the technical feasibility and environmental benefits of adopting circular economy aligned thermal

systems. However, it also draws attention to several ongoing challenges. These include the complexity of integrating multiple technologies into cohesive systems, high initial investment costs, the lack of clear policy incentives, and difficulties associated with optimising system performance across varying operational conditions. Addressing these barriers will be essential for unlocking the full potential of thermal systems within future circular and sustainable energy infrastructures.¹²

Discussion: Integration And Implementation Strategies

System Integration: Multi-Modal Thermal Infrastructure

To fully realise the potential of thermal systems within a circular economy, it is essential to integrate multiple technologies so that they operate as a coordinated and complementary whole. One effective approach involves coupling heat pumps with thermal energy storage systems, which may include sensible storage materials such as water or rock, as well as latent storage options that utilise phase change materials. When these systems are connected to district level thermal networks, they enable large scale energy storage, load shifting, and improved balancing between supply and demand. This makes it possible to align variable renewable energy sources and captured waste heat with the actual heating and cooling needs of buildings throughout the day and across different seasons.

Ground source heat pumps combined with thermal energy storage have consistently demonstrated strong performance and operational stability. Because they draw from the naturally stable temperatures below the earth's surface, these systems offer an attractive low carbon solution for both urban and rural building stock, helping to reduce reliance on fossil fuel based heating technologies.³ Similarly, Earth to Air Heat Exchangers, when used either alongside heat pumps or as part of passive building design strategies, provide an effective means of delivering low energy heating and cooling. Their ability to use the natural thermal properties of the soil allows buildings to pre condition incoming air with minimal mechanical intervention, contributing to significant reductions in overall energy demand.

Beyond building level applications, integrating waste heat recovery with advanced power generation cycles such as the Organic Rankine Cycle offers additional opportunities to enhance energy efficiency. These systems can convert low grade waste heat into electrical power while also supporting heating and cooling needs. Waste to energy technologies further expand the potential of integrated thermal systems by converting municipal and industrial waste streams into useful thermal energy, effectively closing loops of material and energy flow. Such configurations are increasingly viewed as practical realisations of circular economy principles, where waste is minimised and energy

is continuously recovered, reused, and reintegrated into the system.

Environmental And Energy Efficiency Benefits

The adoption of integrated thermal systems has the potential to deliver substantial reductions in primary energy use and greenhouse gas emissions across a wide range of applications. Heat pumps present one of the most effective examples of this improvement. Because they transfer heat rather than generate it directly, they are able to supply several units of heat for every single unit of electricity consumed. In many cases, their coefficient of performance exceeds 3, meaning they can achieve overall energy efficiencies of more than 300 per cent when compared with conventional electric resistance heating. This significant boost in efficiency makes them particularly valuable in both residential and commercial decarbonisation efforts.

Waste heat recovery technologies offer another major opportunity for improving energy performance. When designed and operated effectively, these systems can capture large volumes of thermal energy that would normally be released into the environment. The recovered heat can then be reused for industrial processes, space heating, water heating, or power generation, helping to reduce fuel consumption and associated emissions. As a result, waste heat recovery supports not only energy efficiency improvements but also cost savings and lower environmental impact for industrial sectors.

In a similar way, waste to energy systems contribute to sustainability by addressing two issues simultaneously: waste disposal and energy supply. By converting municipal, industrial, or agricultural waste into usable heat, electricity, or fuel, these systems transform materials that would otherwise require landfilling or incineration into valuable energy resources. This dual role helps ease pressure on waste management infrastructure while contributing to cleaner and more efficient energy generation within a circular economy framework.

Challenges And Barriers

Despite the clear benefits, several challenges continue to impede large-scale deployment of integrated thermal systems:

- **Economic and financial viability:** Many technologies such as heat pumps, thermal energy storage, waste heat recovery units, and waste to energy plants require high initial capital investment. Long payback periods further discourage adoption, particularly in sectors with limited financial flexibility.
- **Technical complexity and integration issues:** Integrating multiple thermal technologies (HP + TES + WHR + WtE) requires sophisticated system design, advanced control strategies, and reliable maintenance.

Temperature mismatches, fluctuating loads, and real-world variability can significantly affect system performance.

- **Policy and regulatory gaps:** In several regions, the absence of comprehensive policies, incentives, and regulatory frameworks slows down the adoption of sustainable thermal technologies. For instance, incentives for high-temperature industrial heat pumps are still limited or only recently introduced.
- **Resource and environmental concerns:** Waste-to-energy processes can generate emissions (CO₂, particulate matter, and other pollutants) if not adequately controlled. Additionally, the heterogeneous nature of waste streams affects combustion characteristics and overall energy conversion efficiency.
- **Limitations of thermal energy storage:** TES systems face challenges such as thermal losses, capacity limitations, performance degradation over time, and geological constraints in ground-based storage systems. These factors reduce their long-term effectiveness and reliability.

Pathways Forward: Framework For Deployment In Circular Economy Contexts

To address these challenges and fully harness the potential of thermal systems for sustainable energy infrastructures, the following strategies are recommended:

- **Policy support and incentives:** Governments should promote the deployment of heat pumps, TES, waste-heat recovery systems, and waste-to-energy facilities through financial incentives such as subsidies, tax reductions, and carbon-pricing mechanisms. Clear regulatory frameworks aligned with circular-economy principles can further accelerate adoption.
- **Holistic planning and system-level design:** Urban planners and engineers should prioritise integrated energy system design at district or community scales—such as district heating and cooling networks or renewable-energy communities—rather than implementing isolated, building-level interventions.
- **Hybrid and flexible system configurations:** Combining complementary thermal technologies (e.g., HP + TES + WHR + WtE) enhances flexibility, improves resilience, and enables the optimal use of thermal resources across varying seasons and demand profiles.
- **Research, development, and innovation:** Continued investment is needed in advanced storage materials (such as next-generation phase-change materials), low-emission waste-to-energy conversion technologies, and intelligent control systems capable of optimising performance under dynamic operating conditions.
- **Public awareness and multi-stakeholder collaboration:** Raising awareness among consumers, industries, and

policymakers can support broader acceptance of circular-economy-driven thermal solutions. Collaboration among sectors—including waste management, building infrastructure, energy services, and environmental agencies—is essential for successful implementation.

Conclusion

Thermal systems including heat pumps, waste heat recovery technologies, thermal energy storage, and waste to energy conversion constitute a robust toolkit for enabling sustainable heating, cooling, and power generation within a circular economy paradigm. The reviewed literature affirms that when these technologies are integrated into well designed, synergistic systems, they can substantially reduce energy consumption, decrease greenhouse gas emissions, divert waste from landfills, and enhance overall resource efficiency.

However, their widespread adoption is still constrained by economic, technical, and policy related barriers. Addressing these challenges will require coordinated and multisectoral efforts, including supportive governmental incentives, coherent regulatory frameworks, holistic district scale energy planning, continued innovation for performance optimisation, and strong stakeholder engagement.

Looking ahead, as renewable energy penetration increases and energy networks become more intelligent and interconnected, thermal systems particularly when paired with advanced storage and smart control mechanisms are expected to play a central role in building sustainable, resilient, and low carbon urban and industrial infrastructures. For researchers, engineers, and policymakers advancing circular economy and sustainability initiatives, these thermal technologies present a promising pathway toward efficient, decarbonised, and resource circular energy systems.

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