STM JOURNALS

International Journal of
Energy and Thermal Applications

Volume 3, Issue 1, 2025
January–June
DOI (Journal): 10.37591/IJETA

https://journals.stmjournals.com/ijeta

Review IJETA

Low-Grade Heat Recovery: Emerging Materials and Systems for Efficient Utilization

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Abstract

Low-grade heat (LGH), generally characterized by temperatures below 200°C, constitutes a significant portion of wasted thermal energy in industrial, commercial, and even residential processes. Despite its vast availability, the efficient recovery and utilization of LGH remains underdeveloped due to its inherently low exergy content and the limitations of traditional heat recovery technologies. The creation of cutting-edge materials and creative system-level approaches for LGH recovery has accelerated significantly as companies continue to look for sustainable and energy-efficient solutions. This review critically examines the current landscape of LGH recovery, emphasizing emerging materials such as thermoelectric compounds, phase change materials, nanofluids, and metal-organic frameworks, all of which offer unique thermal, electrical, or adsorptive properties that enhance energy conversion efficiency. Additionally, system-level technologies such as the Organic Rankine Cycle (ORC), thermoelectric generators, absorption/adsorption cooling, and hybrid thermal conversion mechanisms are analyzed for their performance, integration potential, and practical limitations. The synergy between materials and system design plays a crucial role in improving the viability of LGH recovery across various sectors, including power generation, automotive exhaust recovery, building energy systems, and data center thermal management. The study also explores the techno-economic feasibility, scalability, and lifecycle sustainability of these technologies, while addressing key challenges such as cost, material durability, and operational complexity. Future perspectives are provided, highlighting opportunities for smart monitoring, modular integration, and the role of artificial intelligence in optimizing LGH utilization. Overall, this review offers a comprehensive understanding of how novel materials and engineering innovations are reshaping the potential of low-grade heat recovery and contributing to global energy efficiency goals and decarbonization efforts.

Keywords: Low-grade heat, thermoelectric materials, organic Rankine cycle, phase change materials, waste heat recovery, thermal energy conversion

INTRODUCTION

The global energy landscape is undergoing a rapid transformation driven by increasing energy demands, climate change concerns, and the urgent need for sustainable energy practices. In this context, improving energy efficiency has emerged as one of the most effective strategies to reduce greenhouse gas emissions and minimize energy waste. One particularly underutilized area of energy efficiency is the recovery and reuse of low-grade heat (LGH), which refers to thermal energy with temperatures typically below 200°C. LGH is abundant in industrial processes, transportation systems, power plants, and even in residential and commercial settings. However, its utilization remains limited due to several technical and economic challenges [1, 2].

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Received Date: June 17, 2025
Accepted Date: June 25, 2025
Published Date: July 04, 2025

Citation: Sai Preetham Anumasu. Low-Grade Heat Recovery: Emerging Materials and Systems for Efficient Utilization. International Journal of Energy and Thermal Applications. 2025; 3(1): 24–29p.

Low-grade heat is predominantly released into the environment without being harnessed, representing a significant loss of potentially usable energy. According to estimates, over 50% of industrial waste heat is low-grade in nature, indicating an enormous, yet largely untapped, resource. Typical sources of LGH include exhaust gases from engines, flue gases from boilers and kilns, cooling water from condensers and turbines, solar thermal collectors under diffuse irradiation, and geothermal resources at shallow depths. Despite being widespread, recovering LGH is inherently difficult due to its low thermal potential and limited ability to drive traditional thermodynamic processes efficiently [3, 4].

The key barrier to utilizing LGH lies in its low exergy, which limits the efficiency of conversion to useful work or electricity. Conventional power cycles, such as the steam Rankine cycle, require high-temperature sources and are unsuitable for LGH applications. Consequently, alternative approaches and specialized technologies are necessary to effectively capture and convert low-grade thermal energy. Over the past decade, significant advancements have been made in developing materials and systems tailored for LGH recovery. These innovations aim to overcome the thermodynamic limitations and improve the economic feasibility of low-temperature energy conversion [5, 6].

Emerging materials such as advanced thermoelectric compounds, phase change materials (PCMs), nanofluids, and metal-organic frameworks (MOFs) have shown promise in improving the efficiency of heat capture, storage, and conversion at low temperatures. These materials exhibit unique properties, such as enhanced thermal conductivity, selective heat absorption, and energy storage capabilities, making them suitable for LGH applications. At the systems level, technologies like the organic Rankine cycle (ORC), thermoacoustic engines, absorption chillers, and hybrid systems integrating multiple conversion techniques are being optimized for low-temperature operation and deployed in various pilot and commercial projects [7, 8].

In parallel, there is growing interest in integrating LGH recovery systems into industrial processes, building energy systems, and renewable energy installations. The adoption of such systems not only improves overall energy efficiency but also contributes to reducing fossil fuel consumption and carbon emissions. However, to fully realize the potential of LGH recovery, further efforts are required to address material limitations, system complexity, integration challenges, and cost-effectiveness [9].

This review presents a comprehensive overview of the latest developments in materials and technologies for low-grade heat recovery. It examines the performance, benefits, and limitations of various approaches, while highlighting current trends, case studies, and future research directions aimed at making LGH recovery a mainstream component of sustainable energy systems [10].

SOURCES AND CHALLENGES OF LOW-GRADE HEAT

Low-grade heat (LGH), typically defined as thermal energy below 200°C, is abundant across a variety of industrial, commercial, and natural settings. Although this form of heat is often wasted, it holds significant potential for recovery and reuse if appropriate technologies are applied.

Common Sources

- Exhaust streams from combustion engines and industrial furnaces, which release a considerable amount of thermal energy during operation.
- Cooling water discharged from power plants and HVAC systems, which retains residual heat after thermal exchange.
- Geothermal sources with temperatures below 150°C, commonly found in shallow geothermal reservoirs.
- Solar thermal collectors operating under diffused radiation or ambient conditions, especially in low-insolation regions.

Key Challenges

- Low exergy content limits the overall conversion efficiency into usable energy.

- Difficulty in storing or transporting heat at low temperatures reduces practical applicability.
- Degradation of materials under repetitive thermal cycling or prolonged low-temperature exposure.
- Economic viability and long payback periods hinder widespread adoption of recovery systems.

ADVANCED MATERIALS FOR LOW-GRADE HEAT RECOVERY

Emerging materials play a pivotal role in enhancing the efficiency of low-grade heat (LGH) recovery systems. Their tailored thermal, electrical, and structural properties enable improved energy conversion, storage, and transport, making them integral to next-generation heat recovery technologies.

Thermoelectric Materials (TE)

Thermoelectric materials enable direct conversion of thermal gradients into electrical energy via the Seebeck effect. Recent advancements aim to enhance the thermoelectric figure of merit (ZT) through strategies such as nano-structuring, doping, and alloy engineering. Materials like bismuth telluride (Bi_2Te_3), skutterudites, and half-Heusler compounds demonstrate promising performance at low-to-moderate temperatures.

Phase Change Materials (PCMs)

PCMs store and discharge thermal energy through latent heat during phase transitions. Eutectic salts, paraffin waxes, and metal alloys are being developed for improved thermal conductivity, chemical stability, and long-term cycling reliability, supporting efficient LGH storage and controlled release.

Metal-Organic Frameworks (MOFs)

MOFs are porous crystalline materials offering high surface area, tunable porosity, and excellent thermal stability. Their selective adsorption properties make them ideal for use in LGH-powered adsorption chillers and thermal-driven heat pumps.

Nanofluids and Heat Transfer Fluids

Nanofluids, particularly those containing Al_2O_3 or CuO nanoparticles dispersed in water or organic fluids, significantly enhance convective heat transfer rates in LGH systems. Their superior thermal properties contribute to better system performance, especially in compact and distributed recovery setups.

SYSTEM-LEVEL TECHNOLOGIES

The development of advanced system-level technologies plays a pivotal role in effectively harnessing low-grade heat (LGH). These technologies aim to maximize energy conversion efficiency while maintaining cost-effectiveness and operational reliability.

Organic Rankine Cycle (ORC)

The Organic Rankine Cycle remains one of the most prominent and commercially viable solutions for converting LGH into useful electrical energy. By utilizing organic working fluids with low boiling points, such as R245fa, toluene, or pentane, the ORC can operate efficiently even at source temperatures below 150°C. Its adaptability to various heat sources and modular design makes it suitable for a wide range of industrial and renewable energy applications.

Thermoacoustic Engines

These engines convert thermal energy into acoustic waves and subsequently into electricity using linear alternators. Their design, which involves minimal moving parts, ensures high reliability and low maintenance, making them ideal for continuous operation in remote or unattended settings.

Absorption and Adsorption Chillers

Low-grade heat can be effectively used to drive chillers for space or process cooling. Lithium bromide-water and silica gel-water systems are widely implemented for their compatibility with LGH and low operational cost.

Heat Pipe and Loop Thermosyphon Systems

These passive thermal management systems offer efficient, compact, and maintenance-free operation. Their ability to transfer heat over long distances with minimal thermal loss makes them useful in electronics cooling, solar thermal systems, and waste heat recovery.

Hybrid and Cascade Systems

Integrating multiple conversion technologies, such as coupling ORC with thermoelectric generators (TEGs) or phase change materials (PCMs), can significantly enhance overall energy recovery. These hybrid or cascade systems utilize complementary thermodynamic cycles to optimize performance across different temperature levels.

PERFORMANCE METRICS AND ECONOMIC CONSIDERATIONS

Evaluating low-grade heat (LGH) recovery technologies requires a thorough analysis of both technical and economic performance indicators. These parameters help determine the feasibility and long-term benefits of adopting such systems in industrial and commercial settings.

- *Energy conversion efficiency:* The conversion efficiency of LGH recovery systems is generally limited to below 15%, primarily due to the low temperature and exergy of the heat source. This limitation underscores the necessity for advanced materials with high thermoelectric figure of merit (ZT) and innovative system architectures that can optimize thermal gradients and reduce energy losses.
- *Levelized cost of energy (LCOE):* LCOE serves as a critical metric for evaluating the cost-effectiveness of energy produced over the system’s lifespan. Although initial investments in LGH recovery technologies can be substantial, ongoing developments in materials, manufacturing techniques, and economies of scale are driving LCOE down, making these systems increasingly competitive with conventional energy solutions.
- *Payback period:* The return on investment largely depends on factors such as the size and capacity of the system, the stability and availability of the heat source, and the system's maintenance and operational costs.

RECENT DEVELOPMENTS AND CASE STUDIES

In recent years, significant advancements have been made in the practical deployment of low-grade heat recovery systems, supported by both technological improvements and industrial interest in energy optimization. Several pilot-scale implementations and research-based prototypes have demonstrated the feasibility and benefits of emerging heat recovery technologies in real-world settings.

- *Pilot-scale deployment of ORC units in steel and cement industries has shown promising recovery of 50–200 kW electrical output from flue gases:* These installations, often integrated with existing exhaust systems, demonstrate how waste heat from high-volume, continuous processes can be efficiently converted into usable electrical energy, thus offsetting operational energy demands and reducing greenhouse gas emissions.
- *Development of flexible thermoelectric modules for automotive exhaust recovery:* Researchers have fabricated bendable and robust thermoelectric devices capable of conforming to curved exhaust surfaces. These systems can harvest waste heat directly from vehicle exhausts and convert it into supplementary power for onboard electronics, improving overall vehicle efficiency.
- *Integration of MOF-based chillers in data centers and chemical process cooling:* Metal-organic frameworks with high adsorption capacity are being utilized in compact, LGH-driven cooling systems, helping industries maintain thermal regulation while reducing electricity consumption and enhancing sustainability.

RESEARCH GAPS AND FUTURE DIRECTIONS

Despite notable advancements in low-grade heat recovery technologies, several key research and implementation gaps persist that must be addressed to enable their widespread and effective deployment. One of the primary limitations lies in the scalability of advanced materials, many of which demonstrate excellent laboratory performance but remain impractical for commercial-scale production due to high costs or complex synthesis methods.

- *Material scalability:* Many high-performance materials are not yet scalable or economically viable. Research should focus on cost-effective fabrication techniques and material stability under operational conditions.
- *System integration:* There is a growing need for modular, compact, and plug-and-play systems that can be seamlessly retrofitted into existing industrial setups without significant disruption or redesign.
- *Smart monitoring:* Incorporating smart sensors, real-time diagnostics, and AI-based control systems can enhance efficiency, reliability, and maintenance scheduling, particularly in variable operating environments.
- *Policy support:* Government incentives, clear regulatory frameworks, and supportive policies can significantly influence the adoption rate of LGH recovery systems, especially in energy-intensive manufacturing sectors where the return on investment may be slower.

CONCLUSION

The efficient utilization of low-grade heat (LGH) presents a significant, yet underexploited, opportunity for enhancing global energy efficiency and advancing sustainability goals. Despite the inherent thermodynamic limitations that constrain conversion efficiency at lower temperatures, recent developments in advanced materials and innovative system-level approaches have opened promising avenues for effective LGH recovery. Technologies such as organic Rankine cycles (ORC), thermoelectric generators, and integrated hybrid systems are emerging as front-runners in this evolving landscape. These solutions offer scalable, adaptable, and environmentally friendly options for converting otherwise wasted thermal energy into useful work. However, large-scale implementation will depend on the successful integration of novel materials, robust design methodologies, and cost-effective deployment strategies. To realize the full potential of LGH recovery, the following actions remain critical:

- Advancing interdisciplinary research and development.
- Scaling up pilot demonstrations and industrial trials.
- Formulating supportive regulations and financial incentives.
- Enhancing awareness of low-grade heat utilization across sectors.

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