American Journal of Advanced Multidisciplinary Research and Innovation (AJAMRI)

E-ISSN: XXXX-XXXX • Website: www.ajamri.com • Email: editor@ajamri.com

Heat-to-Electricity Conversion Technologies: Advancing Energy Recovery and Low-Carbon Industrial Systems

Ralph Katz

Lecturer Massachusetts Institute of Technology

Abstract

Industrial processes generate substantial quantities of waste heat, much of which is discharged into the environment despite containing significant recoverable energy. The conversion of waste heat into electricity represents an important pathway for improving industrial energy efficiency, reducing primary energy consumption, and supporting low-carbon manufacturing. Technologies such as thermoelectric generators, organic Rankine cycles, Kalina cycles, supercritical carbon dioxide cycles, thermionic converters, and thermophotovoltaic systems offer different approaches for transforming thermal energy into electrical power. This paper examines the technological foundations, performance characteristics, integration opportunities, economic considerations, and sustainability implications of heat-to-electricity conversion technologies in industrial systems. A conceptual qualitative methodology is adopted to compare major technologies according to temperature range, scalability, efficiency, operational complexity, and application suitability. The analysis indicates that no single technology is optimal across all industrial conditions; rather, technology selection should be based on heat-source temperature, continuity, available thermal power, spatial constraints, and electricity demand. Thermoelectric systems offer compact and relatively simple solutions for distributed low-to-medium-temperature sources, while organic Rankine cycles and advanced thermodynamic cycles are more suitable for larger and higher-temperature applications. Emerging thermophotovoltaic and supercritical carbon dioxide technologies could further expand the usable heat-recovery envelope. The paper proposes an integrated industrial heat-recovery framework combining thermal storage, heat cascading, intelligent monitoring, and electricity generation. It concludes that heat-to-electricity conversion should be integrated into broader industrial decarbonisation strategies rather than treated as an isolated energy-efficiency measure.

Keywords: Waste Heat Recovery, Heat-to-Electricity Conversion, Thermoelectric Generators, Organic Rankine Cycle, Industrial Decarbonisation, Energy Efficiency, Thermophotovoltaics, Supercritical CO_2, Low-Carbon Manufacturing, Energy Recovery.

1. Introduction

Industrialisation has created enormous demand for energy-intensive processes.
Industries such as:

- Steel.
- Cement.
- Glass.
- Chemicals.
- Petrochemicals.
- Refineries.
- Food processing.
- Ceramics.
- Power generation.

operate at a wide range of temperatures.
A significant proportion of the energy entering these processes ultimately leaves as:

- Hot exhaust gases.
- Steam.
- Cooling water.
- Heated process streams.
- Furnace losses.
- Radiative heat.
- Hot solid materials.

Traditionally, much of this energy has been rejected into the atmosphere or cooling systems.
This creates an important opportunity.
Instead of treating waste heat purely as a by-product, industrial systems can treat it as an energy resource.
The basic concept is:

Industrial Fuel/Electricity → Process → Waste Heat → Heat Recovery → Electricity
Heat-to-electricity technologies therefore have the potential to convert otherwise unused thermal energy into useful electrical power.

2. Waste Heat and Industrial Energy Efficiency

Waste heat can originate from almost every energy-intensive industrial operation.
For example, a furnace may generate high-temperature exhaust gases, while a chemical process may release lower-temperature heat through cooling systems.
The recoverability of heat depends on:

- Temperature.
- Flow rate.
- Duration.
- Heat-source stability.

- Chemical composition.
- Accessibility.
- Distance from the conversion system.

Higher-temperature sources generally provide greater opportunities for efficient power generation.

3. Research Objectives

This paper aims to:

1. Examine major heat-to-electricity conversion technologies.
2. Compare their operating principles.
3. Analyse their suitability for different industrial temperature ranges.
4. Examine efficiency and economic considerations.
5. Investigate integration with industrial processes.
6. Assess environmental benefits.
7. Identify technological barriers.
8. Propose an integrated heat-recovery framework.
9. Discuss the role of digital technologies.
10. Identify future research directions.

4. Research Methodology

A conceptual qualitative methodology is used to evaluate heat-to-electricity conversion technologies.

The analysis considers:

- Thermodynamic principles.
- Technology characteristics.
- Industrial applications.
- Energy-efficiency potential.
- Economic considerations.
- Environmental implications.

The technologies are evaluated according to:

Parameter	Evaluation Area
Temperature	Suitable heat-source range
Efficiency	Conversion effectiveness
Scalability	Small-to-large systems
Cost	Capital and operational requirements
Complexity	Maintenance and integration

Parameter	Evaluation Area
Flexibility	Ability to handle variable heat
Sustainability	Emissions and resource implications

5. Thermodynamic Foundation

The fundamental challenge is that heat is not equivalent to electricity.

Thermal energy must pass through a conversion process that produces useful work or electrical output.

For a heat engine, the theoretical maximum efficiency is associated with the temperature difference between the heat source and heat sink.

where:

- Th = absolute temperature of the heat source.
- Tc = absolute temperature of the heat sink.

Actual industrial systems operate below this theoretical limit because of:

- Heat-transfer losses.
- Mechanical losses.
- Electrical losses.
- Irreversibility.
- Pressure losses.
- Auxiliary power consumption.

6. Major Heat-to-Electricity Technologies

The principal technologies include:

1. Thermoelectric generators.
2. Organic Rankine cycles.
3. Kalina cycles.
4. Steam Rankine cycles.
5. Supercritical CO_2 cycles.
6. Thermionic conversion.
7. Thermophotovoltaic systems.
8. Stirling engines.

Each technology has different operating requirements.

7. Thermoelectric Generators

Thermoelectric generators (TEGs) directly convert a temperature difference into electricity using the Seebeck effect.

The basic concept is:

Heat Source → Temperature Gradient → Thermoelectric Material → Electricity

Advantages

- No moving parts.
- Compact.
- Low maintenance.
- Silent operation.
- Suitable for distributed applications.

Limitations

- Relatively low conversion efficiency.
- Material costs.
- Performance depends strongly on temperature difference.

8. Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is one of the most established approaches for converting low- and medium-temperature heat into electricity.

Instead of water, ORC systems use an organic working fluid with a lower boiling point.

The basic cycle consists of:

Evaporation → Expansion → Condensation → Pumping

ORC systems can recover heat from:

- Industrial exhaust.
- Geothermal sources.
- Biomass systems.
- Engine exhaust.
- Solar thermal systems.

9. Kalina Cycle

The Kalina cycle uses a mixture, commonly involving water and ammonia, as its working fluid.

The mixture can provide thermodynamic advantages under certain variable-temperature heat-source conditions.

Potential applications include:

- Industrial waste heat.
- Geothermal systems.
- Combined heat and power.
- Medium-temperature energy recovery.

However, system complexity and working-fluid management can affect implementation.

10. Steam Rankine Cycle

The conventional steam Rankine cycle remains highly relevant for high-temperature waste heat.

It is particularly appropriate when:

- Large heat quantities are available.
- High-temperature exhaust exists.
- Continuous operation is possible.

However, conventional steam systems may be less attractive for smaller or lower-temperature heat sources.

11. Supercritical CO_2 Cycles

Supercritical carbon dioxide cycles represent an emerging technology.

CO_2 can operate above its critical point, enabling compact turbomachinery and potentially high efficiency.

Potential applications include:

- High-temperature industrial heat.
- Concentrated solar thermal systems.
- Nuclear systems.
- Advanced power generation.

Challenges include:

- High operating pressures.
- Materials requirements.
- Turbomachinery development.
- System control.

12. Thermophotovoltaic Conversion

Thermophotovoltaic (TPV) systems convert thermal radiation directly into electricity.

The conceptual process is:

High-Temperature Heat → Thermal Radiation → Photovoltaic Cell → Electricity

TPV technology is particularly interesting for very high-temperature sources.

Potential applications include:

- Industrial furnaces.
- Thermal energy storage.
- High-temperature manufacturing.
- Advanced energy systems.

13. Thermionic Conversion

Thermionic converters generate electricity by releasing electrons from a heated surface.

They are particularly suited to high-temperature environments.

Potential applications include:

- High-temperature industrial systems.
- Space power systems.
- Advanced thermal-energy conversion.

However, materials and operating-temperature requirements remain significant challenges.

14. Stirling Engines

Stirling engines convert external heat into mechanical work through cyclic expansion and compression of a working gas.

They can potentially use:

- Industrial waste heat.
- Solar thermal energy.
- Biomass heat.
- Other external heat sources.

Their main limitation for industrial applications can be system complexity and economic competitiveness compared with other technologies.

15. Temperature-Based Technology Selection

A conceptual classification is:

Heat Source	Potential Technologies
Low temperature	TEG, ORC
Medium temperature	ORC, Kalina, Stirling
High temperature	Steam Rankine, sCO_2
Very high temperature	TPV, thermionic, advanced cycles

Actual technology selection depends on more than temperature alone.

16. Industrial Applications

16.1 Steel Industry

Steel production generates high-temperature exhaust gases and other thermal losses.

Potential applications include:

- Furnace exhaust recovery.
- Coke-oven gas heat recovery.
- Hot-gas power generation.

17. Cement Industry

Cement production involves high-temperature kilns.

Waste heat can originate from:

- Preheater exhaust.
- Clinker cooler.
- Kiln systems.

Waste heat recovery can reduce purchased electricity and improve overall plant efficiency.

18. Glass Manufacturing

Glass furnaces operate at extremely high temperatures.

Heat recovery opportunities include:

- Exhaust gases.
- Furnace surfaces.
- Hot process streams.

High-temperature conversion technologies may therefore be particularly relevant.

19. Chemical and Petrochemical Industries

Chemical processes frequently produce large amounts of thermal energy.

Heat-to-electricity conversion can potentially be integrated with:

- Steam systems.
- Process heaters.
- Distillation systems.
- Reactor cooling.
- Exhaust streams.

20. Refineries

Refineries contain numerous heat-intensive processes.

Waste heat can be recovered from:

- Furnaces.
- Boilers.
- Gas turbines.
- Process streams.

An integrated system can potentially combine electricity generation with process heating.

21. Food Processing

Food industries often produce lower-temperature waste heat.

Examples include:

- Drying.
- Pasteurisation.
- Refrigeration systems.
- Boiler exhaust.

ORC and thermoelectric technologies may have applications where sufficient temperature differences exist.

22. Waste-to-Energy Systems
Municipal and industrial waste-to-energy facilities produce heat through combustion.
Instead of using heat solely for steam production, advanced systems can optimise combined:

Heat + Electricity + Material Recovery
This supports broader circular-economy objectives.

23. Heat Cascading
Not all waste heat should immediately be converted to electricity.
Often, the most efficient approach is:
High-Temperature Heat → Industrial Process → Medium-Temperature Process → Electricity → Low-Temperature Heating
This is called heat cascading.
It can increase the overall value extracted from a thermal resource.

24. Combined Heat and Power
Industrial facilities may combine electricity generation with useful thermal applications.
The system becomes:

Waste Heat → Electricity + Useful Heat
This can improve overall energy utilisation compared with electricity-only generation.

25. Thermal Energy Storage
Waste heat may not always be available when electricity demand is highest.
Thermal energy storage can help decouple:

Heat Availability ≠ Electricity Demand
Storage technologies can include:
- Molten salts.
- Phase-change materials.
- Sensible heat storage.
- Thermochemical storage.

26. Artificial Intelligence for Heat Recovery
Digital technologies can improve heat-recovery systems through:
- Real-time monitoring.
- Predictive maintenance.
- Heat-source forecasting.
- Process optimisation.
- Dynamic load management.

AI can potentially identify operating conditions under which electricity generation provides the greatest economic benefit.

27. Digital Twins

Digital twins can represent industrial heat networks virtually.

They can model:

- Temperature.
- Pressure.
- Flow.
- Energy consumption.
- Equipment performance.

Operators can test different recovery configurations before physically modifying the plant.

28. Smart Heat-Recovery Systems

A future industrial system could include:

Sensors → Data Platform → AI Analytics → Control System → Heat Recovery → Electricity

This converts conventional heat recovery into an intelligent energy-management system.

29. Economic Assessment

The economic feasibility depends on:

- Waste-heat temperature.
- Heat availability.
- Plant operating hours.
- Electricity price.
- Capital expenditure.
- Maintenance costs.
- Conversion efficiency.

A simplified relationship is:

Annual Economic Benefit = Electricity Generated × Electricity Value − Operating Costs

Investment feasibility can then be evaluated through:

- Payback period.
- Net present value.
- Internal rate of return.
- Levelised cost of electricity.

30. Environmental Benefits

Heat-to-electricity conversion can reduce environmental impacts by:

- Recovering otherwise wasted energy.

- Reducing fuel demand.
- Lowering purchased electricity.
- Improving industrial energy efficiency.
- Potentially reducing greenhouse-gas emissions.

The actual emissions reduction depends on what energy source is displaced.

31. Challenges

Major challenges include:

Technical

- Low temperature differences.
- Variable heat sources.
- Corrosive exhaust gases.
- Fouling.
- Material degradation.

Economic

- High initial investment.
- Long payback periods.
- Maintenance costs.

Operational

- Integration with existing plants.
- Limited space.
- Process interruptions.

Environmental

- Working-fluid management.
- Material requirements.
- Lifecycle impacts.

32. Proposed Integrated Industrial Heat-Recovery Framework

This paper proposes a six-stage framework:

Stage 1: Heat Mapping

Identify all waste-heat sources.

Stage 2: Heat Characterisation

Measure:

- Temperature.

- Flow.
- Pressure.
- Duration.
- Chemical composition.

Stage 3: Heat Cascading

Prioritise direct thermal reuse before electricity generation where economically and thermodynamically appropriate.

Stage 4: Conversion

Select:

- TEG.
- ORC.
- Kalina.
- Rankine.
- sCO_2.
- TPV.

Stage 5: Storage

Use thermal storage where heat availability and electricity demand are mismatched.

Stage 6: Intelligent Optimisation

Use sensors, digital twins, and AI to continuously optimise the system.

33. Technology Comparison

Technology	Typical Application	Major Advantage	Major Challenge
TEG	Distributed/low-medium heat	No moving parts	Low efficiency
ORC	Low-medium heat	Mature technology	Working-fluid issues
Kalina	Variable medium heat	Thermodynamic flexibility	Complexity
Rankine	High-temperature heat	Established	Larger infrastructure
sCO_2	High-temperature heat	Compact potential	High pressure
TPV	Very high temperature	Direct conversion	Materials/cost
Thermionic	Very high temperature	Direct electricity generation	High-temperature materials

Technology	Typical Application	Major Advantage	Major Challenge
Stirling	External heat	Flexible heat source	Mechanical complexity

34. Research and Innovation Priorities

Future research should focus on:

1. High-performance thermoelectric materials.
2. Advanced ORC working fluids.
3. Compact sCO_2 turbomachinery.
4. High-temperature photovoltaic materials.
5. Advanced thermal storage.
6. AI-enabled heat optimisation.
7. Digital twins.
8. Integrated industrial energy systems.
9. Low-cost heat exchangers.
10. Modular conversion systems.

35. Policy Recommendations

Governments and industry should:

- Introduce incentives for industrial waste-heat recovery.
- Establish energy-efficiency standards.
- Support demonstration projects.
- Fund advanced conversion technologies.
- Encourage industrial energy audits.
- Develop financing mechanisms for retrofits.
- Promote low-carbon industrial parks.
- Encourage heat-sharing networks.

36. Future Directions

36.1 Hybrid Conversion

Future systems may combine multiple technologies.

For example:

High-Temperature Heat → sCO_2/Rankine → Low-Temperature Heat → ORC/TEG

This can increase total energy recovery.

36.2 AI-Controlled Energy Networks

AI could dynamically select whether heat should be:

- Reused.
- Stored.

- Converted into electricity.
- Exported.

36.3 Modular Systems

Containerised heat-recovery units could make deployment easier for small and medium-sized industries.

36.4 Industrial Energy Networks

Factories may eventually exchange waste heat and electricity through interconnected industrial energy networks.

37. Questionnaire

Scale: 1 = Strongly Disagree, 5 = Strongly Agree

No.	Statement
1	Industrial waste heat represents a significant untapped energy resource.
2	Heat-to-electricity systems can improve industrial energy efficiency.
3	ORC technology is suitable for many industrial waste-heat applications.
4	Thermoelectric generators can support distributed heat recovery.
5	Advanced sCO_2 systems can improve high-temperature energy recovery.
6	Thermal storage can improve the economic performance of waste-heat systems.
7	AI can improve the operation of industrial heat-recovery systems.
8	Heat recovery can contribute to industrial decarbonisation.
9	Government incentives are important for large-scale adoption.
10	Integrated heat-recovery systems will become an important component of future low-carbon industries.

38. Discussion

Heat-to-electricity conversion should not be evaluated solely according to electrical efficiency.
A system that converts waste heat into a relatively small quantity of electricity may still provide substantial value if the heat would otherwise be completely wasted.
Conversely, direct heat reuse may sometimes provide greater overall energy savings than converting the heat into electricity.
Therefore, the optimal strategy should consider the complete industrial energy system.
The concept of heat cascading is particularly important.

High-quality thermal energy should ideally be used for applications requiring high temperatures, while lower-quality heat can subsequently be used for lower-temperature processes or electricity generation.
This approach maximises the useful energy extracted from the original heat source.

39. Conclusion

Heat-to-electricity conversion represents an important opportunity for improving the efficiency and sustainability of industrial energy systems.
Technologies such as thermoelectric generators, organic Rankine cycles, Kalina cycles, steam Rankine systems, supercritical CO_2 cycles, thermophotovoltaics, and thermionic converters provide different pathways for recovering electricity from otherwise wasted thermal energy.
No single technology is appropriate for every application.
Instead, technology selection should consider:

- Heat-source temperature.
- Thermal capacity.
- Operating duration.
- Heat variability.
- Capital cost.
- Electricity prices.
- Integration requirements.
- Environmental impacts.

The greatest opportunity lies in moving from isolated waste-heat recovery systems towards intelligent, integrated industrial energy ecosystems.
A future low-carbon industrial facility could therefore operate according to:
Heat Generation → Heat Cascading → Thermal Storage → Electricity Conversion → Intelligent Optimisation
By combining advanced conversion technologies with AI, digital twins, thermal storage, and industrial energy networks, waste heat can become an important component of industrial energy resilience.
Ultimately, heat-to-electricity conversion should not be regarded merely as a method of recovering lost energy. It can become a strategic component of low-carbon industrial transformation, resource efficiency, and the development of more intelligent and resilient energy systems.

References

1. International Energy Agency. (2019). Energy Efficiency 2019. IEA.
2. International Energy Agency. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. IEA.
3. U.S. Department of Energy. (2004). Waste Heat Recovery: Technology and Opportunities in U.S. Industry. U.S. Department of Energy.

4. Forman, C., Muritala, I. K., Pardemann, R., & Meyer, B. (2016). Estimating the global waste heat potential. Renewable and Sustainable Energy Reviews, 57, 1568–1579.
5. Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, S. A. (2018). Waste heat recovery technologies and applications. Thermal Science and Engineering Progress, 6, 268–289.
6. Tchanche, B. F., Lambrinos, G., Frangoudakis, A., & Papadakis, G. (2011). Low-grade heat conversion into power using organic Rankine cycles: A review of various applications. Renewable and Sustainable Energy Reviews, 15(8), 3963–3979.
7. Quoilin, S., Van Den Broek, M., Declaye, S., Dewallef, P., & Lemort, V. (2013). Techno-economic survey of organic Rankine cycle systems. Renewable and Sustainable Energy Reviews, 22, 168–186.
8. Chen, H., Goswami, D. Y., & Stefanakos, E. K. (2010). A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. Renewable and Sustainable Energy Reviews, 14(9), 3059–3067.
9. He, J., & Tritt, T. M. (2017). Advances in thermoelectric materials research: Looking back and moving forward. Science, 357(6358), eaak9997.
10. Champier, D. (2017). Thermoelectric generators: A review of applications. Energy Conversion and Management, 140, 167–181.
11. Lecompte, S., Huisseune, H., van den Broek, M., Vanslambrouck, B., & De Paepe, M. (2015). Review of organic Rankine cycle architectures for waste heat recovery. Renewable and Sustainable Energy Reviews, 47, 448–461.
12. Wang, E. H., Zhang, H. G., Fan, B. Y., Ouyang, M. G., Zhao, Y., & Mu, Q. H. (2011). Study of working fluid selection of organic Rankine cycle for engine waste heat recovery. Energy, 36(5), 3406–3418.
13. Angelino, G., & Colonna, P. (2000). Air and other gases as working fluids for organic Rankine cycles. International Journal of Thermodynamics.
14. Sarkar, J. (2015). Second law analysis of supercritical CO_2 recompression Brayton cycle. Energy, 84, 363–370.
15. Crespi, F., Gavagnin, G., Sánchez, D., & Martínez, G. S. (2017). Supercritical carbon dioxide cycles for power generation: A review. Applied Energy, 195, 152–183.