Open Horizon Scientific Review

Vol. 04 No.01 2026

Optimization of Waste Heat Recovery Systems in Energy-Intensive Industries

Muhammad Zayyan Farooq

Department of Mechanical Engineering, Faisalabad, Pakistan

ABSTRACT

Energy-intensive industries discharge thermal energy through exhaust gases, cooling systems, hot products, wastewater, and equipment surfaces. Recovering part of this energy can reduce purchased utilities and improve industrial resource efficiency. However, the quantity of available heat alone does not determine the suitability of a recovery project. Temperature, contamination, operating schedules, heat demand, equipment constraints, and economic conditions influence its practical value. This narrative review examines the optimization of industrial waste heat recovery through source characterization, thermodynamic analysis, process integration, technology selection, equipment design, operational control, and economic assessment. Particular attention is given to heat exchanger networks, organic Rankine cycles, industrial heat pumps, thermal storage, and the effects of fouling and pressure losses. An integrated optimization framework is proposed in which useful energy delivery and lifecycle performance are evaluated under realistic operating conditions. A theoretical graph illustrates how source temperature affects the maximum reversible work obtainable from heat supplied by an isothermal reservoir; it does not represent actual recovery-system efficiency. The review argues that effective optimization should prioritize avoidable heat-loss reduction, suitable source–sink matching, and reliable operation before pursuing maximum equipment output. Application-specific measurements, uncertainty analysis, and verification of realized savings are essential for translating theoretical potential into durable industrial benefits.

Key words: *Waste heat recovery, Process integration, Exergy analysis, Industrial energy efficiency, Thermoeconomic optimization*

Introduction:

Energy-intensive industries depend on substantial thermal inputs for material transformation, separation, drying, melting, and chemical processing. Cement manufacturing, iron and steel production, glassmaking, refining, chemicals, and pulp and paper operations provide prominent examples. A portion of their energy input leaves the production system as heat that is not subsequently used.

Waste heat recovery captures this thermal energy and transfers or converts it into a useful service. Possible applications include combustion-air preheating, feedwater heating, process heating, steam generation, cooling, and electricity production. The suitability of each application depends on the

characteristics of the heat source and the requirements of the receiving process.

A large waste heat stream does not necessarily constitute an attractive investment. Heat may be available at an unsuitable temperature, contain corrosive substances, occur intermittently, or be located far from a useful demand. Conversely, a smaller stream can provide substantial value when it closely matches a continuous process requirement.

Forman and colleagues distinguish the scale of waste heat resources through a global estimation approach, while Papapetrou and colleagues examine technically available industrial resources by sector, temperature, and location. These studies support separating broad resource estimates from the recoverable and economically useful heat available at a particular facility (Forman et al., 2016; Papapetrou et al., 2018).

Optimization therefore requires more than selecting a recovery device. It involves defining system boundaries, measuring source conditions, identifying suitable sinks, comparing technologies, and evaluating performance across operating conditions. Decisions must also account for maintenance, production reliability, and future changes in industrial processes.

This article presents a narrative review and conceptual framework rather than an experimental investigation. Nine sections explain how thermodynamic, operational, and economic considerations can be integrated to optimize waste heat recovery in energy-intensive industries.

1. Characterization of Industrial Waste Heat Sources

A reliable optimization study begins with a structured inventory of heat sources. Relevant information includes temperature, mass flow, composition, pressure, physical phase, operating duration, and variability. Measurements should represent normal production, reduced load, start-up, shutdown, and other recurring operating modes.

For a single-phase stream with approximately constant specific heat capacity, available sensible heat can be estimated from mass flow, specific heat, and the allowable temperature reduction. Where phase changes occur or properties vary substantially, an enthalpy-based calculation is more appropriate.

The allowable outlet temperature is an engineering constraint rather than an arbitrary target. Exhaust cooling may be limited by condensation, corrosion, stack performance, or downstream equipment requirements. Cooling a process stream too aggressively may also interfere with production or increase another utility demand.

Source quality extends beyond temperature. Dust, sticky deposits,

moisture, corrosive constituents, and fluctuating composition can influence equipment selection and maintenance. A clean liquid stream and a particle-laden exhaust stream may require very different recovery arrangements even when their thermal duties are similar.

Heat availability should be expressed as a time-dependent profile. Multiplying the maximum heat rate by total annual hours can substantially overestimate useful recovery when production or heat demand is intermittent. Source and sink measurements should therefore be aligned in time.

Jouhara and colleagues review industrial recovery technologies across different source conditions and applications. Their work supports evaluating heat quantity, quality, and physical characteristics together when identifying suitable recovery options (Jouhara et al., 2018).

A source inventory should also distinguish unavoidable residual heat from losses that can first be reduced. Improved insulation, combustion control, or process redesign may reduce the heat available for recovery while improving overall efficiency. Recovery equipment should be sized against the improved process where such changes are planned.

2. Thermodynamic Assessment and Exergy-Based Optimization

Energy analysis establishes the quantity of thermal energy entering and leaving the system. It is necessary for calculating recovery duties and checking balances, but it does not fully describe the ability of heat to perform useful work.

Exergy analysis introduces this quality dimension by relating energy to a reference environment. Heat supplied at a higher temperature generally has greater potential to produce work than the same quantity supplied near ambient temperature. Nevertheless, low-temperature heat can still be valuable when it meets a suitable heating demand directly.

For reversible conversion of heat supplied by an isothermal reservoir, the maximum work fraction is expressed by the Carnot relationship, using absolute temperatures. This relationship provides an upper bound, not an achievable efficiency for an industrial recovery installation.

A finite hot stream cools as energy is extracted. Its work potential must therefore account for the changing temperature rather than applying the inlet-temperature Carnot factor to all recovered heat. Real equipment introduces additional losses through finite temperature differences, pressure

drops, mechanical inefficiencies, and auxiliary power consumption.

Exergy analysis can identify where useful potential is destroyed. Large temperature differences during heat transfer and unnecessary mixing of streams at different temperatures may indicate opportunities for improved integration. However, reducing every thermodynamic loss may require uneconomic equipment expenditure.

Optimization should consequently balance thermodynamic improvement with capital cost and operational feasibility. A design with slightly lower exergy efficiency may be preferable if it is more reliable, easier to maintain, or better suited to variable production.

3. Process Integration and Heat Source–Sink Matching

Waste heat becomes useful when an appropriate receiving demand is available. Source–sink matching should consider temperature compatibility, heat duty, operating schedule, physical distance, and process constraints. A technically recoverable stream may have limited value if no suitable demand exists when the heat is available.

Direct process reuse should be evaluated before more complex conversion arrangements. For example, using suitable exhaust heat to preheat an incoming stream can avoid conversion losses associated with producing electricity and subsequently using that electricity for heating. This is an evaluation priority rather than a universal rule.

Pinch analysis provides a systematic approach to identifying heat recovery targets and utility requirements. It examines the temperature–enthalpy relationships of process streams and supports the design of integrated heat exchanger networks. The foundational method developed by Linnhoff and Hindmarsh remains relevant to industrial heat integration (Linnhoff & Hindmarsh, 1983).

The minimum temperature approach influences both recovery and equipment size. A smaller approach can permit greater heat exchange but generally requires more transfer area. The preferred value depends on utility costs, heat transfer characteristics, equipment costs, and practical constraints.

Site-wide integration may reveal that heat currently rejected from one process could serve another. However, integration should not create unacceptable operational dependence. A production interruption in one unit should not necessarily force shutdown of another unit that has become reliant on recovered heat.

Batch and time-dependent processes require additional analysis. A source and sink may be compatible thermally but unavailable

simultaneously. Storage, intermediate loops, or revised schedules may improve compatibility, although each introduces costs and losses.

Kemp and Smith provide broader process integration methods for evaluating these relationships. Their approaches support treating recovery equipment as part of the production and utility system rather than as an isolated addition (Kemp, 2007; Smith, 2016).

4. Selection of Waste Heat Recovery Technologies

Technology selection should follow the identified source and sink conditions. Recuperators, regenerators, economizers, heat pipe exchangers, and waste heat boilers provide different methods of transferring heat. Their suitability depends on temperature, contamination, pressure requirements, and the receiving service.

Recuperators transfer energy continuously between separated streams. Regenerators store heat temporarily in a medium and subsequently release it to another stream. Economizers commonly recover heat for liquid heating, while waste heat boilers can generate steam where sufficient temperature and suitable operating conditions exist.

Organic Rankine cycles offer a route for converting suitable heat sources into power. Their performance depends on source temperature, cooling conditions, working fluid, cycle arrangement, and component efficiencies. The fluid must also satisfy relevant safety, environmental, and material compatibility requirements.

Quoilin and colleagues review ORC systems from a technical and economic perspective, while Lecompte and colleagues compare cycle architectures for recovery applications. Together, these studies support evaluating the complete cycle and its application conditions rather than selecting an arrangement solely from nominal efficiency (Quoilin et al., 2013; Lecompte et al., 2015). Bianchi and De Pascale (2011) also compare bottoming-cycle options for low- and medium-temperature heat sources.

Industrial heat pumps provide another option by upgrading lower-temperature heat to a useful delivery temperature. Their electricity demand must be included in the assessment. Performance depends strongly on the temperature lift, refrigerant, compressor arrangement, and operating conditions.

Arpagaus and colleagues examine high-temperature heat pumps and their application potential. Their review supports considering heat pumps where direct heat exchange cannot provide the required temperature, while avoiding assumptions that all temperature lifts are equally attractive (Arpagaus et al., 2018).

The selected technology should remain compatible with the plant's maintenance capabilities and operating practices. A theoretically superior device may be unsuitable if it requires unavailable expertise, difficult replacement parts, or operating conditions the facility cannot maintain.

5. Heat Exchanger Design and Equipment-Level Optimization

Heat exchangers frequently determine the practical effectiveness of recovery systems. Their design must provide the required thermal duty while respecting pressure loss, material compatibility, fouling, mechanical integrity, and maintenance requirements.

Increasing heat transfer area can improve recovery, but it also increases cost and space requirements. Higher flow velocities may improve heat transfer while raising pressure losses and erosion risk. Equipment optimization must therefore consider thermal and hydraulic behavior together.

For dirty exhaust streams, geometry should allow effective cleaning and inspection. Narrow passages may provide compact equipment but become unsuitable where deposits accumulate rapidly. Removable sections, access points, and appropriate surface arrangements can improve long-term performance.

Fouling changes the preferred design. An exchanger optimized for clean initial operation may lose useful output quickly if deposits reduce heat transfer and restrict flow. A realistic analysis should evaluate performance over the cleaning cycle rather than at commissioning alone.

Material selection is particularly important where condensation or corrosive compounds may occur. Lowering outlet temperature can increase recovered energy while introducing corrosion or condensate-management requirements. These consequences should be assessed before assigning additional savings.

Auxiliary energy must also be included. Fans and pumps may consume more electricity after the recovery system introduces additional resistance. The useful benefit is the reduction in purchased energy or increase in valuable output after these penalties are considered.

Equipment-level optimization should preserve process performance. Increased furnace backpressure, altered drying conditions, or reduced ventilation can outweigh recovery benefits if product quality or throughput deteriorates. The production process remains the primary service that the recovery system must support.

6. Operational Control and Thermal Energy Storage

Industrial recovery systems rarely operate continuously at one design point.

Variations in throughput, source temperature, ambient conditions, and receiving demand influence equipment performance. Operational optimization should therefore evaluate a range of conditions.

Control variables may include bypass position, circulation rate, heat delivery temperature, pump speed, and power-cycle operating pressure. Their selection should maintain process requirements while maximizing useful recovery within equipment limits.

A bypass can protect the main process during start-up, equipment cleaning, or recovery-system failure. Although bypass operation reduces recovered energy, it can improve overall availability and reduce the operational risk associated with tightly integrated equipment.

Thermal storage can reduce mismatches between heat availability and demand. Sensible storage, latent storage, and other arrangements offer different temperature characteristics and operational requirements. Selection should consider useful temperature range, charging and discharging rates, losses, and cycling behavior.

Storage does not create additional heat. Its value arises from making existing heat available at a more useful time. Oversized storage may add investment and heat losses without providing proportional benefit when annual source and demand profiles are already poorly matched.

Control optimization should distinguish useful delivery from gross collection.

Collecting more heat into storage provides limited benefit if the receiving process cannot subsequently use it. Performance indicators should therefore track delivered energy and displaced utilities.

Model-based control can support coordinated operation, but its predictions depend on the quality of source forecasts and equipment models. Practical implementation should include reliable fallback control and monitoring of deviations between predicted and measured behavior.

7. Mathematical Optimization and Uncertainty Analysis

An optimization model should define its objective, decision variables, constraints, and system boundary explicitly. Possible objectives include maximizing net present value, minimizing lifecycle cost, reducing fuel consumption, or balancing cost with emissions reduction.

Decision variables can include exchanger area, network arrangement, storage capacity, working-fluid selection, cycle pressures, and operating schedules. Some variables are continuous, while equipment selection

and stream connections may require discrete decisions.

Constraints should represent physical and operational requirements. These include energy balances, allowable temperatures, pressure losses, equipment capacity, minimum operating loads, and limits needed to protect production quality.

Different mathematical methods suit different problem structures. Linear approximations can support screening, nonlinear models can represent detailed thermodynamic behavior, and mixed-integer formulations can combine equipment selection with sizing. Heuristic methods may help explore complex designs but do not automatically establish global optimality.

Uncertainty analysis is essential because future production, utility costs, heat demand, and equipment degradation are not known exactly. Evaluating one favorable scenario can produce a design that performs poorly under modest changes in operation.

Sensitivity analysis identifies variables with the strongest influence on results. Scenario analysis can examine distinct operating conditions, while probabilistic methods can represent justified input distributions. The choice should reflect available evidence rather than the apparent sophistication of the method.

A robust design may sacrifice some expected benefit to perform acceptably across a wider range of conditions. This can be especially valuable when production schedules change or a receiving process may be modified during the project's lifetime.

8. Economic and Environmental Performance Assessment

Economic assessment should compare the recovery project with a clearly defined baseline. That baseline should include planned efficiency improvements and realistic future operation, rather than assuming that avoidable losses continue unchanged.

Capital expenditure includes more than the recovery device. Installation, ductwork, piping, controls, civil works, grid connection where relevant, and production downtime can materially affect cost. Operating expenditure includes maintenance, cleaning, consumables, auxiliary electricity, and replacement parts.

Simple payback is useful for preliminary screening, but it does not fully represent project life, financing, maintenance timing, or changes in benefits. Discounted cash-flow analysis provides a more complete view when its assumptions are stated transparently.

Recovered thermal energy should not be equated directly with avoided fuel input. If recovered heat replaces useful heat from a boiler, the displaced fuel

depends on the boiler's efficiency and actual operating response. If the boiler remains at minimum load or continues operating inefficiently, realized savings may differ from the initial estimate.

Environmental assessment should similarly use the actual displaced energy source. Electricity consumption by a heat pump and auxiliary systems must be included. Recovery projects can also affect water demand, working-fluid impacts, and maintenance materials.

The U.S. Department of Energy identifies technical and practical barriers to industrial recovery, while its technology assessment places recovery within wider industrial efficiency opportunities. These sources support evaluating implementation conditions alongside theoretical potential (U.S. Department of Energy, 2008, 2015).

Financial and environmental conclusions should remain application-specific. A project that reduces fuel use may not deliver the same emissions benefit under every electricity supply or operating arrangement. Avoiding double counting between recovered heat, generated power, and displaced utilities is essential.

9. Industrial Implementation and Performance Verification

Implementation should proceed from measurement and screening to detailed engineering, installation, commissioning, and ongoing verification. Each stage should resolve uncertainties that could change equipment selection or expected value.

Retrofit projects require careful attention to layout and construction access. Existing equipment, limited space, shutdown windows, and structural constraints may restrict an otherwise attractive design. Early involvement of operations and maintenance personnel can reveal these limitations before detailed design is completed.

Commissioning should confirm thermal duty, pressure losses, control response, protection functions, and interactions with production. Performance at one favorable condition is insufficient where the plant operates across a wide range of loads.

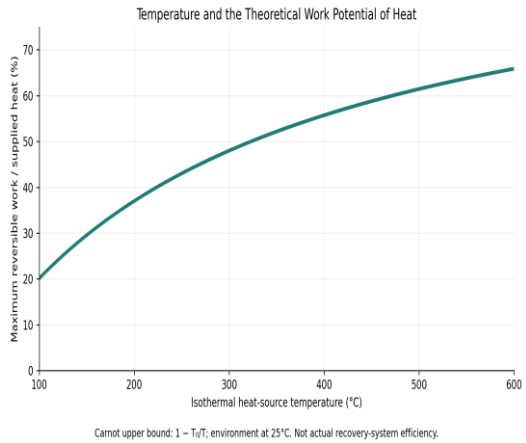
Verification should compare measured outcomes with an adjusted baseline. Production volume, product mix, ambient conditions, and operating hours can change energy consumption independently of the recovery project. These influences should be accounted for when assessing realized savings.

Long-term monitoring should identify fouling, leakage, declining transfer performance, and increased auxiliary power. Maintenance decisions can then be based on the relationship between lost recovery, cleaning cost, and production availability.

For energy-intensive facilities in Pakistan, assessments should use locally

measured sourceprofiles, actual utility costs, available maintenance capabilities, and realistic production schedules. Imported performance assumptions should be checked against site conditions before investment decisions are made.

The integrated framework proposed here begins with reducing avoidable losses, proceeds through source–sink matching and technology comparison, and ends with verified lifecycle performance. Optimization remains an ongoing activity as plant conditions and energy systems change.



Summary

Waste heat recovery can improve industrial energy performance when available heat is matched with a useful demand through suitable equipment and reliable operation. The quantity of rejected heat alone is not enough to establish technical or economic feasibility.

The article emphasizes source characterization as the foundation of optimization. Temperature, flow, composition, variability, and allowable cooling limits determine what can realistically be recovered. Measurements should distinguish unavoidable residual heat from losses that can first be reduced through process improvement.

Energy and exergy analyses provide complementary information. Energy balances quantify thermal duties, while exergy analysis describes useful work potential relative to the environment. The accompanying graph illustrates this temperature dependence through a reversible upper bound; it does not predict actual recovery-system efficiency.

Process integration connects heat sources with appropriate sinks. Pinch analysis, network design, and time-dependent matching can reveal opportunities that isolated equipment selection overlooks. Direct heat reuse, power generation, heat pumping, and storage should be compared according to the service they deliver.

Equipment design must include fouling, corrosion, pressure losses, auxiliary energy, and maintenance access. Operational controls should respond to changing plant conditions while protecting production. Mathematical optimization is most useful when its constraints and uncertainties reflect these practical requirements.

Economic and environmental evaluations should use transparent baselines and actual utility displacement. Recovered energy must not be counted as savings unless it replaces purchased energy or provides another valuable service. Installation costs, downtime, maintenance, and future operating changes can determine whether theoretical benefits are realized.

The central conclusion is that successful waste heat recovery depends on coordinated thermodynamic, process, equipment, operational, and financial decisions. Measurement and verification throughout the project lifecycle are necessary to convert available thermal resources into durable industrial value.

References:

- Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., & Bertsch, S. S. (2018). High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy, 152, 985–1010. https://doi.org/10.1016/j.energy.2018.03.166
- Bianchi, M., & De Pascale, A. (2011). Bottoming cycles for electric energy generation: Parametric investigation of available and innovative solutions for the exploitation of low and medium temperature heat sources. Applied Energy, 88(5), 1500–1509. https://doi.org/10.1016/j.apenergy.2010.11.013
- Forman, C., Muritala, I. K., Pardemann, R., & Meyer, B. (2016). Estimating the global waste heat potential. Renewable and Sustainable Energy Reviews, 57, 1568–1579. https://doi.org/10.1016/j.rser.2015.12.192
- 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. https://doi.org/10.1016/j.tsep.2018.04.017
- Kemp, I. C. (2007). Pinch analysis and process integration: A user guide on process integration for the efficient use of energy (2nd ed.). Butterworth-Heinemann.
- Lecompte, S., Huisseune, H., van den Broek, M., Vanslambrouck, B., & De Paepe, M. (2015). Review of organic Rankine cycle (ORC) architectures for waste heat recovery. Renewable and Sustainable Energy Reviews, 47, 448–461. https://doi.org/10.1016/j.rser.2015.03.089
- Linnhoff, B., & Hindmarsh, E. (1983). The pinch design method for heat exchanger networks. Chemical Engineering Science, 38(5), 745–763. https://doi.org/10.1016/0009-2509(83)80185-7

- Papapetrou, M., Kosmadakis, G., Cipollina, A., La Commare, U., & Micale, G. (2018). Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country. Applied Thermal Engineering, 138, 207–216. https://doi.org/10.1016/j.applthermaleng.2018.04.043
- Quoilin, S., van den Broek, M., Declaye, S., Dewallef, P., & Lemort, V. (2013). Techno-economic survey of organic Rankine cycle (ORC) systems. Renewable and Sustainable Energy Reviews, 22, 168–186. https://doi.org/10.1016/j.rser.2013.01.028
- Smith, R. (2016). Chemical process design and integration (2nd ed.). John Wiley & Sons.
- U.S. Department of Energy. (2008). Waste heat recovery: Technology and opportunities in U.S. industry. https://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf
- U.S. Department of Energy. (2015). Waste heat recovery systems. In Quadrennial technology review 2015 (Technology Assessment 6M). https://www.energy.gov/quadrennial-technology-review-2015-omnibus