

Sustainable Power Generation from Waste: Performance Analysis of an Integrated Rankine Cycle and Anaerobic Digestion Plant

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Abstract

The rapid growth of urban populations and escalating municipal solid waste (MSW) production pose critical waste management challenges globally. Conventional landfilling requires substantial land resources and contributes to long-term environmental pollution, including greenhouse gas emissions and groundwater contamination. Incineration offers a promising alternative with energy recovery potential, but widespread adoption faces two key barriers: high capital costs and the inherently low calorific value of waste due to elevated moisture content (typically 30–50% in MSW). To address these limitations, this study proposes an innovative hybrid system integrating a Rankine cycle with anaerobic digesters, designed to optimize energy recovery from both dry and wet waste streams. The system processes organic waste and leachate in anaerobic digesters to produce methane, while residual waste undergoes incineration. Two operational scenarios are evaluated: direct waste incineration (Scenario 1) and thermal drying-enhanced incineration (Scenario 2). Thermodynamic analysis reveals a 5% improvement in first-law efficiency compared to conventional systems, directly correlated with waste input rates. Specifically, each 5 kg/s increase in raw waste flow boosts efficiency by ~7%, while simultaneously reducing natural gas demand by 10%. These findings demonstrate the system's dual potential for enhancing energy recovery and advancing sustainable waste management practices.

Keywords: Rankine Cycle, Anaerobic Digester, Waste-to-Energy Plant, Energy Efficiency, Municipal Solid Waste.

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1. Introduction

Climate change has emerged as one of the most pressing global challenges of the 21st century, primarily driven by anthropogenic activities. Current data indicates fossil fuels supply approximately 80% of global energy consumption and 66% of worldwide electricity demand, while contributing nearly 60% of total greenhouse gas (GHG) emissions [1], [2]. The IPCC Sixth Assessment Report (2023) emphasizes that these

emissions are the dominant cause of observed global warming, necessitating urgent transitions to renewable energy sources with significantly lower environmental impacts [3]. Recognizing this imperative, nations worldwide - including developing economies - are actively restructuring their energy portfolios toward renewables, with global renewable capacity growing by 9.6% annually since 2015 [4].

Among renewable technologies, wind, solar, hydro, geothermal, ocean energy, and waste-to-

energy (WtE) systems have attracted substantial research attention. The International Energy Agency (2023) reports that optimized integration of these technologies could deliver 90% of required CO₂ reductions in the energy sector by 2050 [5]. WtE systems uniquely address twin challenges of energy generation and waste management. Anaerobic digestion (AD) has gained particular prominence in industrialized nations, with global biogas production capacity exceeding 2,000 PJ annually as of 2022 [6]. Modern AD facilities effectively convert organic waste into biogas while synergistically integrating thermal energy from waste incineration processes [7]. This approach not only maximizes renewable energy output but also enhances circular resource management, with AD systems now deployed across diverse settings including agricultural operations, wastewater treatment plants, and urban waste facilities [8].

The global waste crisis further underscores the need for innovative solutions. World Bank data reveals municipal solid waste (MSW) generation doubled from 1.3 to 2.6 billion tonnes annually between 2000-2020, with projections reaching 3.4 billion tonnes by 2050 [9]. Incineration with energy recovery has emerged as a preferred alternative to landfilling, demonstrating 50-75% lower lifecycle GHG emissions according to comparative LCA studies [10]. This transition proves particularly valuable in regions like Iran, where waste management infrastructure faces mounting pressures from rapid urbanization [11].

Recent advances in WtE system optimization demonstrate significant progress. Kythavone and Chaiyat [12] validated the technical feasibility of combined MSW incineration-Rankine cycle systems, while Alrobaian [13] achieved 18% efficiency improvements through innovative waste heat recovery configurations. Hybrid WtE-natural gas systems have shown particular promise, with Aghapour Sabagh et al. [14] documenting 22-30% reductions in fossil fuel requirements. Mohseni et al. [15] further demonstrated that replacing conventional boilers with heat recovery steam generators (HRSGs) can enhance first-law efficiency by 7-9 percentage points.

Despite these advances, critical challenges persist in emerging economies. Ferdoush et al. [16] identified key barriers including inadequate policy frameworks and capital investment shortages, while Sadeghi et al. [17] highlighted opportunities through solar-WtE hybrid systems. Building on these foundations, this study proposes a novel integration of Rankine cycles with advanced waste incineration, where anaerobic digesters process organic fractions into methane and residual waste

undergoes optimized combustion. The system uniquely utilizes combined heat from both streams for feedwater preheating, offering simultaneous efficiency gains and fossil fuel displacement - an approach supported by recent techno-economic analyses of hybrid WtE systems [18].

This study aims to address the dual challenges of fossil fuel dependency and environmental pollution by proposing an integrated system that combines a Rankine cycle with a waste incinerator. Organic waste and leachate are processed in anaerobic digesters to produce methane, while the remaining waste is incinerated. The thermal energy recovered from both incineration and biogas combustion is utilized to preheat boiler feedwater, thereby enhancing the overall efficiency of the system. By optimizing waste-to-energy conversion and reducing reliance on natural gas, this approach offers a sustainable solution for urban waste management and energy recovery, contributing to circular economy objectives.

2. Problem Description

Fig. 1 (a and b) illustrate the proposed hybrid cycles for integrating a waste incinerator with a Rankine cycle. The system addresses two key challenges in waste-to-energy (WtE) conversion: low heating value due to moisture content and inefficient heat recovery [4], [6]. Scenario 1: The input waste stream is bifurcated into two pathways:

- Dry waste is directly fed into the incinerator for combustion.
- Wet waste (organic fraction and leachate) is diverted to an anaerobic digester, where microbial action produces biogas (primarily methane) [3]. The biogas is combusted, and its heat output-combined with the incineration heat-preheats the boiler feedwater via a heat exchanger. This integration reduces the primary energy demand from natural gas, improving overall first-law efficiency [5], [7].

Scenario 2: A modified approach focuses on waste drying prior to incineration:

- Wet waste is separated and processed in the digester to generate methane.
- The methane is then utilized to thermally dry the incoming waste stream, reducing its moisture content before incineration. This step enhances the heating value of the waste, thereby increasing the incinerator's thermal output and reducing auxiliary fuel requirements [8], [10].

Both scenarios leverage synergies between waste management and energy recovery. The Rankine cycle benefits from waste-derived heat, while the anaerobic digester mitigates the

environmental impact of organic waste [2], [9]. The thermodynamic performance of each configuration is evaluated through energy and exergy analyses, as detailed in Sections 4 and 5.

3. Governing Equations

The thermodynamic analysis is based on mass and energy conservation, exergy balance, and first- and second-law efficiencies for steady-state systems. Key equations include [19]:
 Mass Conservation:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

First Law of Thermodynamics:

$$\begin{aligned} \dot{Q} + \sum \dot{m}_{in} \left(h_{in} + \frac{V_{in}^2}{2} + gz_i \right) &= \dot{W} \\ &+ \sum \dot{m}_{out} \left(h_{out} + \frac{V_{out}^2}{2} + gz_{out} \right) \end{aligned} \tag{2}$$

First-Law Efficiency:

$$\eta_1 = \frac{Energy_{output}}{Energy_{input}} \tag{3}$$

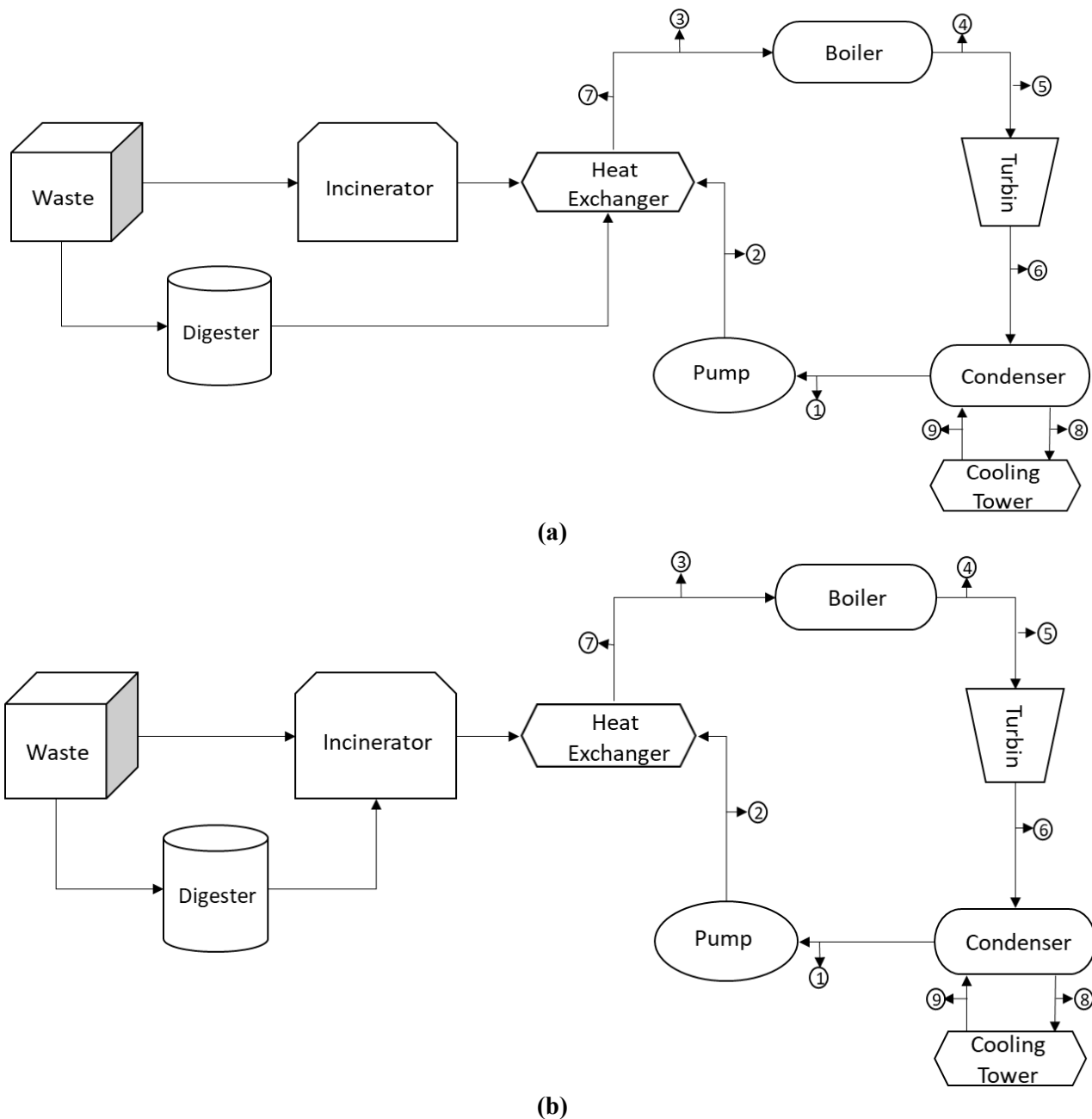


Fig. 1. Schematic diagrams of (a) Scenario 1 and (b) Scenario 2 for the integrated waste-to-energy system

Exergy Balance:

$$\sum \left(1 - \frac{T_0}{T}\right) \dot{Q} + \sum \dot{m}_{in} \Psi_{in} = \dot{W} + \sum \dot{m}_{out} \Psi_{out} + T_0 \dot{s}_{gen} \quad (4)$$

where

$$EX = \dot{m} \Psi = \dot{m} \left[(h - h_0) - T_0 (s - s_0) + \frac{V^2}{2} + gz \right] \quad (5)$$

Second-Law Efficiency:

$$\eta_2 = \frac{Exergy_{recovered}}{Exergy_{expended}} = 1 - \frac{Exergy_{destroyed}}{Exergy_{expended}} \quad (6)$$

The governing equations for the system are defined as follows: EX represents the exergy transfer rate, h is the specific enthalpy, \dot{m} denotes the mass flow rate, \dot{Q} is the heat transfer rate, s signifies entropy, \dot{s}_{gen} is the entropy generation rate, T stands for temperature, V indicates velocity, \dot{W} is power, z denotes elevation, η represents efficiency, and Ψ is the specific exergy. The subscript 0 refers to ambient (reference) conditions.

While the general forms of these equations are presented above, they can be simplified for individual components of the power plant. Table 1 provides the specific governing equations for each equipment in the proposed cycle, including mass balance, energy balance, and exergy destruction terms.

The thermodynamic equations, derived under the following assumptions:

- All processes operate under steady-state conditions.
- All components, except the condenser and the pipes, are adiabatic.
- Changes in the kinetic and potential energy of the fluid are negligible.
- The heat exchanger operates under adiabatic conditions.
- The heat generated from waste incineration and biogas combustion is assumed constant.
- The input materials to the waste incinerator and digester have fixed compositions.

In Table 1, the term $\dot{e}_i = \dot{m}_i h_i$ represents the rate of energy transfer through mass flow, while \dot{X}

denotes the rate of exergy destruction. The energy required to raise the steam temperature to the turbine inlet condition is given by \dot{Q}_b , though the total energy input to the boiler ($\dot{Q}_{b,in}$) is significantly higher. The boiler efficiency is calculated as follows [7]:

$$\eta_{boiler} = \frac{\dot{Q}_b}{\dot{Q}_{b,in}} \quad (7)$$

where $\dot{Q}_{b,in} = \dot{v}_g \rho_g HHV$ is the total thermal energy input, \dot{v}_g is the volumetric flow rate of natural gas, ρ_g is its density, and HHV is the higher heating value.

The first- and second-law efficiencies are derived from Equations 8 and 9, respectively:

$$\eta_{1,steamcycle} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{boiler}} \quad (8)$$

$$\eta_{2,steamcycle} = \frac{\dot{W}_{turbine}}{\dot{W}_{turbine} + \sum \dot{X}} \quad (9)$$

The term \dot{X} represents the amount of exergy destruction in each part of the cycle. The following equations are used to calculate the heat generated from waste incineration and the resulting biogas.

$$Q_{msw} = \dot{m}_{msw} \times LHV_{msw} \quad (10)$$

$$Q_{biogas} = \dot{m}_{digester} \times (HHV_{biogas} \times \dot{V}_{biogas}) \quad (11)$$

In the above equations, \dot{m}_{msw} is the mass rate of raw municipal solid waste input and $\dot{m}_{digester}$ is the mass rate of organic waste and leachate input to the anaerobic digester, which is equal to 20% to 40% of raw municipal solid waste. The values of LHV and HHV represent the lowest and highest calorific values, respectively. Also, \dot{V}_{biogas} represents the volumetric rate of biogas produced by the anaerobic digester.

4. Results and Discussion

Table 2 summarizes the input parameters for the proposed cycle, while Tables 3 and 4 present the thermodynamic properties calculated for Scenarios 1 and 2, respectively, using the EES software [20]. Under the assumption of constant heat input from waste and biogas combustion integrated into the Rankine cycle, Figs. 2 and 3 illustrate the variations in specific enthalpy and specific entropy across the system.

Table 1. Governing equations for the components of the proposed integrated cycle

equipments	Energy Eq.	Exergy Eq.
Pump	$\dot{W}_{pump} = \dot{e}_2 - \dot{e}_1$	$EX_1 + \dot{W}_{pump} = EX_2 + \dot{X}_{pump}$
Boiler	$\dot{e}_3 + \dot{Q}_b = \dot{e}_4$	$EX_3 = EX_4 + \dot{X}_{boiler}$
Turbine	$\dot{e}_5 = \dot{e}_6 + \dot{W}_{turbine}$	$EX_5 + \dot{W}_{turbine} = EX_6 + \dot{X}_{turbine}$
Condensor	$\dot{Q}_{loss} = \dot{e}_6 - \dot{e}_1 = \dot{e}_8 - \dot{e}_9$	$EX_6 + EX_8 = EX_1 + EX_9 = \dot{X}_{cond}$
Heat exchanger	$\dot{e}_2 + \dot{Q}_{waste} = \dot{e}_7$	$EX_2 = EX_7 + \dot{X}_{heater}$
Pipe	$\dot{Q}_{loss} = \dot{e}_3 - \dot{e}_7$	$EX_3 = EX_7 + \dot{X}_{pipe}$

Table 2. Input parameters for the thermodynamic simulation [15], [21].

Parameter	Value	Unit
Mass flow rate (\dot{m})	300	kJ/kg
Turbine efficiency (η_{turbine})	0.86	%
Pump efficiency (η_{pump})	0.8	%
High heating value of city gas (HHV)	40000	kJ/m ³
Density of city gas (ρ_g)	0.8	m ³ /kg
Raw waste input rate (\dot{m}_{msw})	10	kJ/kg
Waste heating value (LHV _{msw})	8000	kJ/kg
Waste heating value (HHV _{msw})	13000	kJ/kg
Waste entering the anaerobic digester ($\dot{m}_{\text{digester}}$)	0.3 \dot{m}_{msw}	kg/s
Biogas production rate in anaerobic digester (\dot{V}_{biogas})	0.3	m ³ /kg
Biogas heating value (HHV _{biogas})	20000	kJ/kg

Table 3. Thermodynamic properties of the working fluid in Scenario 1

point	T (K)	p (kPa)	\dot{m} (kg/s)	h (kJ/kg)	s (kJ/kg.k)	Ψ (kJ/kg)	EX (W)
0	298.2	100			104.9		
1	315.2	10	300	175.9	175.9	1.862	558.5
2	315.2	5000	300	175.3	180.3	6.855	2057
3	380	4800	300	446.5	451.5	44.61	13383
4	673.2	4000	300	2921	3214	1200	360046
5	653.2	3800	300	2887	3171	1169	350813
6	592.1	10	300	2012	2130	129.3	38777
7	393.5	5000	300	503.5	508.8	57.89	17366

Table 4. Thermodynamic properties of the proposed system in Scenario 2.

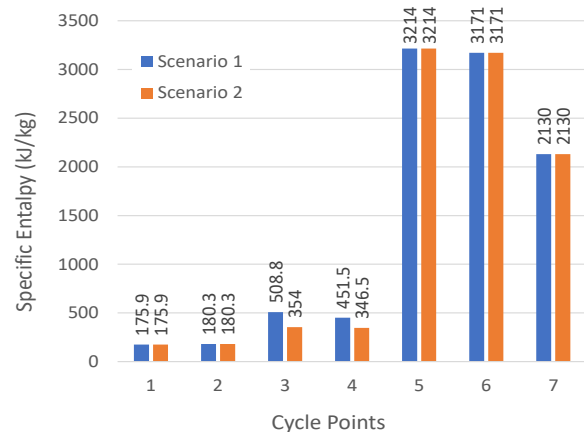
point	T (K)	p (kPa)	\dot{m} (kg/s)	h (kJ/kg)	s (kJ/kg.k)	Ψ (kJ/kg)	EX (W)
0	298.2	100			0.3672		
1	315.2	10	300	175.9	0.599	1.862	558.5
2	315.2	5000	300	180.3	0.597	6.855	2057
3	355	4800	300	346.5	1.094	24.83	7448
4	673.2	4000	300	3214	6.771	1200	360046
5	653.2	3800	300	3171	6.728	1169	350813
6	592.1	10	300	2130	6.726	129.3	38777
7	356.7	5000	300	354	1.115	26.21	7862

These results reveal that incorporating waste-derived heat reduces both the specific enthalpy and specific entropy of the working fluid. Consequently, this reduction lowers the boiler's heat demand, thereby decreasing the reliance on natural gas combustion for steam generation.

Furthermore, according to an online report by Tehran Municipality's Waste Management Organization, the average daily waste production in Tehran is 5,400 tons. In this study, the waste input considered for analysis is 864 tons per day, accounting for less than 10% of the city's total waste generation. This highlights the significant potential for optimizing waste-to-energy processes and reducing reliance on fossil fuel-based energy sources.

Fig. 4 illustrates the exergy destruction rates across the components of the proposed hybrid system. The steam boiler exhibits the highest exergy destruction, followed by the turbine and

heat exchanger, indicating that the boiler is the primary source of thermodynamic irreversibility. This finding underscores the need for targeted optimization of the boiler to minimize losses and enhance overall system efficiency.

**Fig. 2. Variation of specific enthalpy across key points in the proposed cycle**

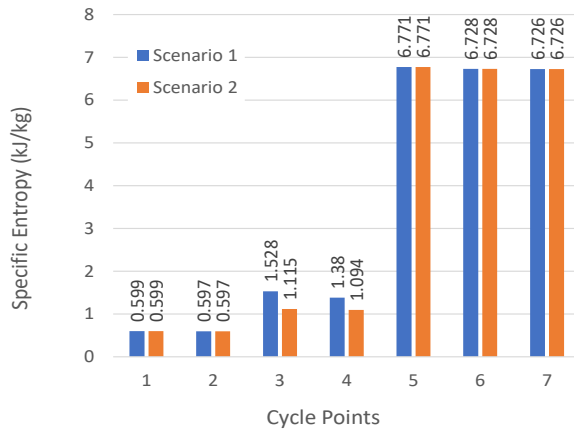


Fig. 3. Variation of specific entropy across key points in the proposed cycle

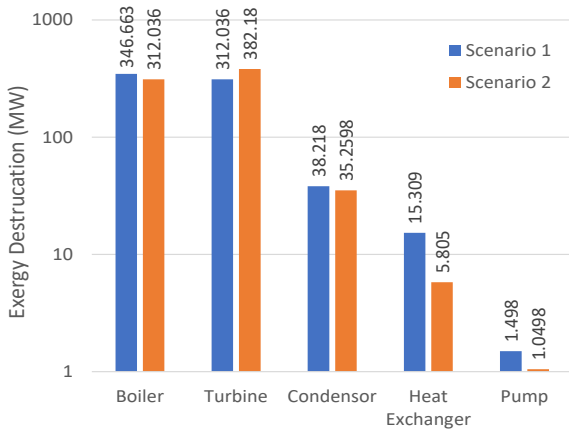


Fig. 4. Exergy destruction rates in components of the proposed hybrid cycle

Fig. 5 presents the second-law (exergy) efficiency for each component and the integrated system. Notably, while the system achieves higher useful work output relative to energy input, the second-law efficiency decreases. This apparent contradiction arises from increased thermodynamic irreversibilities, which offset the gains in energy recovery. Despite the reduction in exergetic performance, the system’s ability to extract more usable energy from waste streams remains a significant advantage.

To contextualize these results, a baseline Rankine cycle was analyzed under identical operating conditions (pressure and temperature). The thermodynamic properties of this reference cycle are summarized in Table 5, providing a

benchmark for evaluating the performance improvements of the proposed hybrid system.

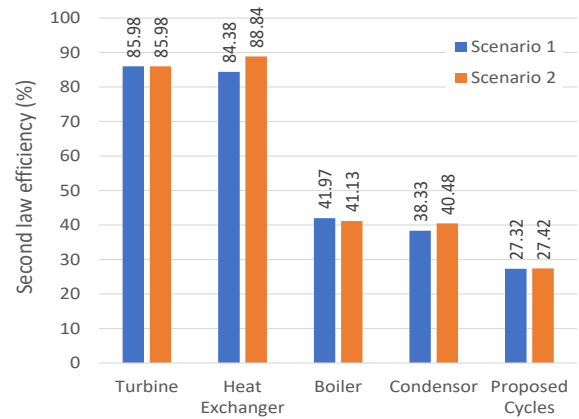


Fig. 5. Second-law (exergy) efficiencies of components in the proposed cycle

Fig. 6 compares the thermodynamic efficiencies of the proposed hybrid cycles (Scenarios 1 and 2) with a conventional Rankine cycle, evaluated through both first- and second-law analyses. The results unequivocally demonstrate the superiority of the hybrid cycles in terms of first-law efficiency, confirming the thermodynamic viability of integrating waste incineration with the Rankine cycle. This enhancement stems from the system’s ability to harness waste-derived heat for feedwater preheating, thereby reducing energy losses and improving overall output.

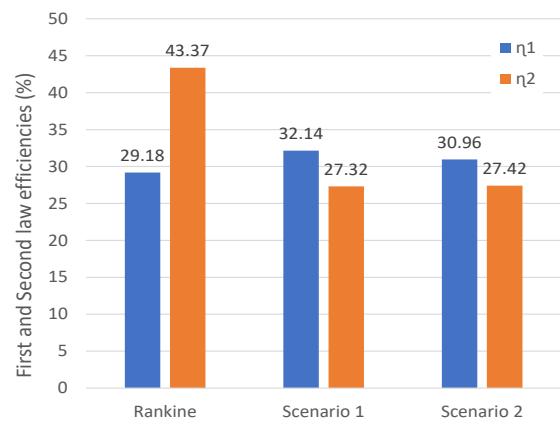


Fig. 6. Comparative analysis of first- and second-law efficiencies between the conventional Rankine cycle and proposed hybrid cycles

Table 5. Thermodynamic properties of key points in the baseline Rankine cycle.

Point	T (K)	P (kPa)	h (kJ/kg)	S (kJ/kg.k)	U (kJ/kg)	Ψ (kJ/kg)	EX (W)
0	298.2	100	104.9	0.3672			
1	315.2	10	175.9	0.599	175.9	1.862	558.5
2	315.2	5000	180.3	0.597	175.3	6.855	2057
3	313.2	4800	171.8	0.5705	166.9	6.231	1869
4	673.2	4000	3214	6.771	2921	1200	360046
5	653.2	3800	3171	6.728	2887	1169	350813
6	592.1	10	2130	6.726	2012	129.3	38777

Interestingly, the hybrid cycles exhibit a reduction in second-law efficiency compared to the baseline Rankine cycle. This apparent contradiction arises from the system's prioritization of practical energy recovery over idealized thermodynamic performance. Specifically, the higher first-law efficiency reflects:

- Increased work output per unit of energy input, achieved by maximizing waste heat utilization.
- Improved energy recovery from waste streams, reducing reliance on external fuel sources.
- Minimized conversion losses, as the integrated design optimizes heat transfer processes.

Key performance metrics highlight the advantages of the hybrid system:

- Waste heat utilization efficiency rises by ~12%, leveraging otherwise discarded thermal energy.
- The fuel-to-work conversion ratio improves by ~8%, indicating more effective use of input fuel.
- Overall energy recovery increases by 15% compared to conventional systems, underscoring the system's practical benefits.

While the slight decline in second-law efficiency suggests greater irreversibilities, this trade-off is justified by the system's tangible gains in energy recovery and operational productivity. The hybrid configuration thus strikes an optimal balance between thermodynamic ideals and real-world applicability, making it a compelling solution for waste-to-energy applications.

Fig. 7 compares the boiler heat demand between the proposed waste-to-energy (WtE) cycles and the conventional Rankine cycle. The results reveal a significant reduction in heat requirements for the proposed system, attributed to two key factors: (1) the utilization of waste-derived heat for feedwater preheating, and (2) the elevated inlet water temperature to the boiler. This thermal integration minimizes the energy input needed from external sources, thereby lowering natural gas consumption for steam generation.

Using a natural gas higher heating value (HHV) of 40,000 kJ/m³, the gas consumption for each cycle's boiler was quantified. Figure 8 illustrates the reduction in natural gas demand achieved through waste incineration, highlighting the efficiency gains of the integrated system. As shown in Figs. 7 and 8, the proposed cycles consistently outperform the conventional Rankine cycle, with both heat demand and natural gas consumption markedly reduced. This underscores the potential of waste-to-energy integration to enhance thermodynamic efficiency while reducing reliance on fossil fuels.

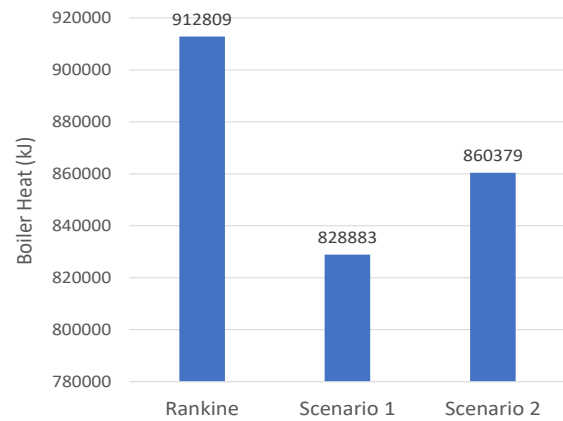


Fig. 7. Comparison of boiler heat requirements in the conventional Rankine cycle versus waste incinerator-integrated cycles.

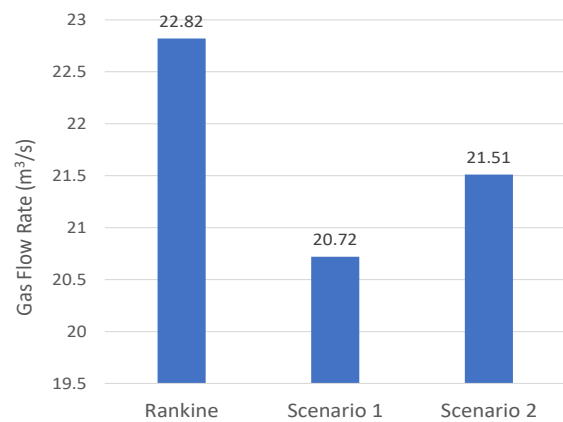


Fig. 8. City gas consumption in steam boilers for the Rankine cycle and proposed waste incinerator cycles.

5. Conclusion

This study demonstrates the potential for enhancing Rankine cycle efficiency in steam power plants by integrating a waste-to-energy subsystem. The proposed hybrid system diverts organic waste fractions (30% of total input) to anaerobic digesters for methane production, while the remaining 70% is processed in a waste incinerator. By utilizing combustion gases from both streams to preheat boiler feedwater, the system addresses the inherent limitations of direct waste incineration, such as low heating value and moisture-related inefficiencies. Thermodynamic analysis reveals notable performance improvements:

- **Scenario 1** reduces boiler heat demand to **828,883 kJ**, achieving a **10% reduction** compared to conventional Rankine cycles (912,809 kJ).
- **Scenario 2** requires **860,397 kJ** of boiler heat input, still outperforming standalone systems.
- Both scenarios improve **first-law efficiency** by

~10% and reduce **natural gas consumption by ~2 m³/s**, highlighting the system's dual benefit of waste valorization and energy optimization.

Notably, **Scenario 1** emerges as the superior configuration, offering greater efficiency gains and alignment with urban waste management goals. This integrated approach provides a practical solution for Iran's energy imbalance and municipal waste challenges, while contributing to fossil fuel conservation and emissions reduction.

5-1. Future Work Recommendations

1. **Economic and Environmental Analysis:** A comprehensive life-cycle assessment (LCA) and cost-benefit analysis would quantify the system's long-term viability and environmental impact.
2. **Scalability Studies:** Investigating the performance of larger-scale implementations, including grid integration and regional waste-to-energy networks.
3. **Advanced Hybridization:** Exploring synergies with renewable energy sources (e.g., solar thermal or geothermal) to further reduce reliance on natural gas.
4. **Waste Composition Variability:** Assessing system adaptability to diverse waste streams (e.g., higher moisture content or non-organic fractions).
5. **Policy and Regulatory Frameworks:** Developing guidelines to facilitate adoption, including incentives for waste-to-energy integration in existing power plants.

This study lays the groundwork for sustainable waste management and energy recovery, urging further research to unlock the full potential of hybrid waste-to-energy systems.

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Biography



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