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Thermodynamic and Environmental Assessment of a Tri-Generation Power Plant Utilizing Municipal Solid Waste

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1. ABSTRACT

In this study, a detailed thermodynamic and carbon dioxide emission analysis was carried out for an integrated biomass-fueled tri-generation system that simultaneously produces electricity, desalinated water, and cooling. The main novelty of the new proposed configuration lies in its combined use of urban solid waste as fuel to generate three useful energy outputs, improving overall efficiency and reducing CO₂ emissions compared with previous studies. Results from the baseline simulation show that the system can supply 4,994 kW of net electrical power, 1,034 kW of equivalent cooling, and 11,960 kg/h of desalinated water with a recovery rate of 33.28%. The calculated overall energy and electrical efficiencies were 73.82 and 39.92%, respectively. To further explore performance improvements, a set of parametric analyses was carried out. The results indicate that increasing the gas turbine inlet temperature and optimizing the evaporation pressure in the organic Rankine cycle can lead to additional gains in output power, cooling capacity, and thermal utilization, while also reducing specific CO₂ emissions. Overall, the findings confirm that the proposed tri-generation system represents a sustainable, efficient, and regionally adaptable solution, particularly well suited for coastal areas, islands, and small-to-medium-scale industrial or residential communities where waste management, water scarcity, and energy demand intersect.

Keywords: Biomass, Thermodynamic efficiency, Absorption refrigeration, Tri-generation; Desalination.

2. INTRODUCTION

In recent decades, growing concerns over global warming, energy security and environmental degradation drive a worldwide shift toward sustainable and renewable energy systems. The ongoing energy crisis, depletion of fossil fuel reserves, and increasing greenhouse gas emissions motivate researchers and policymakers to prioritize clean, low-carbon energy solutions. Among various renewable resources, biomass attracts significant attention due to its wide availability, renewability, low operational cost, and near carbon-neutral nature. Unlike fossil fuels, biomass can be replenished over short time scales, and the CO₂ released during its combustion is largely reabsorbed through the natural carbon cycle, resulting in minimal net contribution to global warming. Consequently, biomass currently represents one of the largest renewable energy potentials worldwide and ranks among the top primary energy sources.

In recent years, numerous studies investigate combined cooling, heating, and power (CCHP) systems driven by renewable energy sources, particularly biomass and hybrid biomass-solar configurations. These studies primarily focus on thermodynamic modeling and energy-exergy performance evaluation, demonstrating that integrated systems can significantly enhance overall efficiency compared with conventional single-generation plants. However, most existing

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works concentrate on dual-generation schemes and often overlook the simultaneous integration of energy, water, and cooling production, as well as the combined optimization of thermal performance and environmental impact [1].

The present study addresses these gaps by proposing and analyzing an integrated biomass-based tri-generation system that simultaneously produces electricity, desalinated water, and cooling. The proposed configuration employs urban solid waste as the primary fuel, providing both an effective waste management strategy and a sustainable energy source. In this system, gas turbine exhaust heat is cascaded to drive an Organic Rankine Cycle and a thermal desalination unit, while low-grade residual heat is recovered for absorption cooling. This stepwise energy recovery enhances overall efficiency and substantially reduces carbon emissions. Furthermore, a dual-parameter analysis investigates the effects of gas turbine inlet temperature and ORC evaporation pressure on system performance and CO₂ intensity. The proposed system is particularly suitable for coastal and island regions, offering a practical, sustainable, and environmentally friendly solution for integrated energy and water production.

3. PROCESS DESCRIPTION AND SIMULATION

The proposed integrated process configuration consists of a gas turbine cycle, an Organic Rankine Cycle using n-octane as the working fluid, a water-ammonia absorption refrigeration cycle, and a double-effect thermal desalination system. These subsystems are thermally and functionally integrated to enable stepwise energy recovery and multi-product generation. Municipal solid waste (MSW) is directly fed into the combustor, where expanded air from the gas turbine provides the required oxidant. Complete combustion of biomass generates high-temperature flue gas, which transfers heat to the compressed air in an air heater and subsequently supplies thermal energy to the ORC evaporator. The n-octane working fluid exits the evaporator as superheated vapor and expands through the ORC turbine to generate electricity. Residual heat from the ORC is recovered through a recuperator and a secondary evaporator, which enhances cycle efficiency and partially condenses the working fluid prior to pumping. The recovered heat from the ORC drives a water-ammonia absorption refrigeration cycle. In this cycle, the working solution is heated, separated into vapor and liquid phases, and expanded to produce low-temperature refrigeration in the evaporator, delivering chilled water at 5 °C. Simultaneously, rejected heat from the absorption system is utilized for thermal integration with the desalination unit. The desalination system operates in two flashing stages. In the first stage, seawater is preheated using flue gas heat and partially flashed under reduced pressure. In the second stage, the remaining brine undergoes further evaporation in a low-pressure evaporator, increasing freshwater recovery. The generated vapor streams from both stages are condensed to produce desalinated water. This cascaded utilization of thermal energy significantly improves overall efficiency and reduces waste heat losses [2].

The proposed system is simulated under steady-state conditions using Aspen HYSYS v12.1. Complete conversion of biomass in the combustor is assumed, and the control volume approach is adopted for thermodynamic analysis. The isentropic efficiencies of the pump, compressor, and turbines are assumed to be 75%, 85%, and 85%, respectively. Heat losses and pressure drop in system components are neglected, and all separator outlet streams are considered saturated. The seawater salinity is fixed at 35,000 ppmw. Boundary conditions, including inlet temperatures and pressures of major streams, are defined based on operational data and relevant literature. Heat exchanger performance is evaluated using the Kern method embedded in HYSYS and validated against reported experimental correlations. Model convergence is achieved using the successive substitution algorithm with a maximum of 50 iterations and a convergence tolerance of 10⁻⁴. Mass and energy balances are verified to ensure simulation accuracy.

Thermodynamic properties are calculated using the Peng–Robinson equation of state, which provides reliable predictions for single-, two-, and three-phase systems across a wide range of operating conditions. This property package is selected based on the process conditions, component characteristics, and subsystem requirements of the integrated tri-generation system.

3.1. Validation of the Proposed System

Since no identical system has been reported in previous studies, the proposed configuration is validated at the subsystem level. The Organic Rankine Cycle, gas turbine, and thermal desalination units are validated using performance data available in the literature. These data are implemented as input conditions in Aspen HYSYS, and simulations are conducted under similar operating conditions. The simulated results are then compared with the corresponding literature values, and the relative deviations are evaluated. The results show very small deviations, confirming the accuracy of the simulation model and the suitability of the selected equation of state for modeling the proposed system [3].

4. RESULTS AND DISCUSSION

4.1. Simulation Results of the Proposed Process

Based on the baseline simulation, the system consumes 12,510 kW of biomass energy and produces 4,994 kW of net electrical power, 1,034 kW of equivalent cooling (corresponding to 45,960 kg/h of chilled water at 5 °C), and 11,960 kg/h of desalinated water with a recovery ratio of 33.28%.

The overall first-law efficiency and electrical efficiency are calculated as 73.82 and 39.92%, respectively. The integrated absorption refrigeration system, thermally coupled with the Organic Rankine Cycle, achieves a coefficient of performance (COP) of 1.08. The results indicate that the proposed configuration exhibits higher energy efficiency compared with similar systems reported in the literature.

From an environmental perspective, the CO₂ footprint of the integrated system is estimated at 0.2 kg CO₂/kWh, which represents a significant reduction relative to previous studies. These findings demonstrate a strong correlation between



thermal integration and environmental performance. Accordingly, the proposed system simultaneously improves energy efficiency and reduces environmental impacts, highlighting its potential as a sustainable energy solution.

4.2. Sensitivity Analysis of the Proposed System

A parametric sensitivity analysis is conducted to evaluate the performance of the proposed system. Three key parameters are selected due to their dominant influence on the overall energy balance: the ORC recuperator outlet temperature, the gas turbine inlet air temperature, and the ORC turbine inlet pressure. These parameters directly affect heat transfer rates, turbine enthalpy differences, and net power output (Figure 1).

From a first-law perspective, variations in temperature and pressure significantly influence the enthalpy changes across major components, leading to changes in energy efficiency. From a second-law viewpoint, higher inlet temperatures increase the availability of useful work and reduce exergy losses within the thermally integrated subsystems. Increasing the ORC working fluid temperature at the recuperator outlet enhances cooling capacity by intensifying heat transfer in the absorption cycle, while slightly reducing desalinated water production due to lower exhaust gas temperatures entering the seawater heater. As a result, the overall energy efficiency shows a moderate increase, although electrical power generation remains unchanged. Raising the gas turbine inlet air temperature increases both electrical power and cooling output, leading to a notable improvement in overall energy efficiency and a simultaneous reduction in CO₂ emission intensity. Similarly, increasing the ORC turbine inlet pressure enhances turbine power output, net electrical generation, and electrical efficiency, while reducing the carbon footprint due to higher product generation at constant fuel input [4].

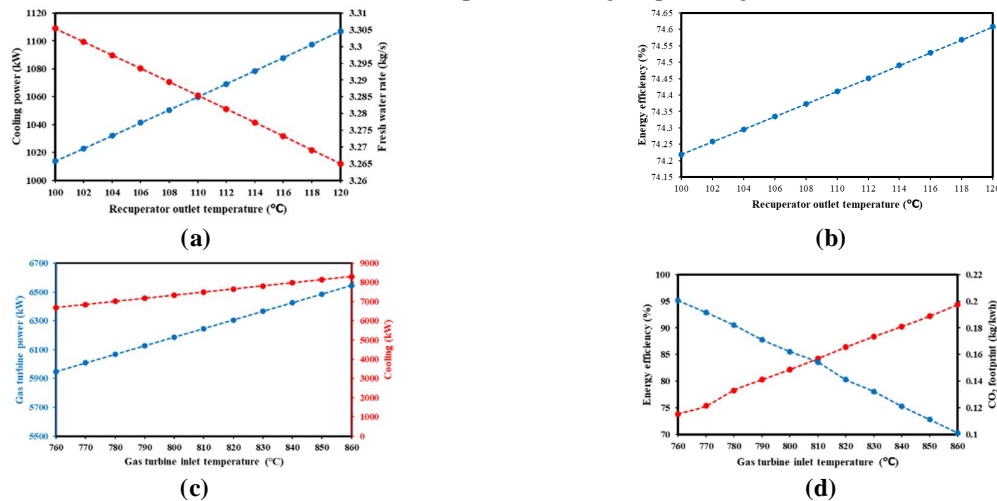


Figure 1. Evaluating the effect of key parameters on the overall energy balance of the proposed system

5. CONCLUSION

This study investigates a novel integrated power plant fueled by municipal solid waste through thermodynamic and environmental analyses. The proposed system combines a gas turbine cycle, an Organic Rankine Cycle, an absorption refrigeration cycle, and a two-stage thermal desalination unit in a cascaded heat recovery structure. The main contributions include a new plant configuration, improved thermodynamic integration, higher overall energy efficiency, and a notable reduction in CO₂ emission intensity compared to similar systems. The influence of key operating parameters on system performance is also evaluated.

Future work may focus on enhancing sustainability by integrating solar energy with biomass, assessing alternative ORC working fluids under different climatic conditions, and replacing thermal desalination with membrane-based technologies such as reverse osmosis. Additionally, economic, life cycle, and scalability analyses are recommended to support practical deployment in coastal, island, and small industrial applications.

6. REFERENCES

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