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Performance characterization of a power generation unit–organic Rankine cycle system based on the efficiencies of the system components

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ABSTRACT

This paper analyzes the potential of using the waste heat from a power generation unit to generate additional electricity using an organic Rankine cycle to reduce operational cost, primary energy consumption, and carbon dioxide emissions in different locations in the U.S. The power generation unit–organic Rankine cycle system is compared with a conventional system in terms of operational cost, primary energy consumption, and carbon dioxide emissions reduction. A parameter (R_{min}), which is based on system efficiencies, is established to determine when the proposed power generation unit–organic Rankine cycle system would potentially provide savings versus the conventional system in which electricity is purchased from the utility grid. The effect on the R_{min} parameter with variation of each system efficiency is also analyzed in this paper. Results indicated that savings in one parameter, such as primary energy consumption, did not imply savings in the other two parameters. Savings in the three parameters (operational cost, primary energy consumption, and carbon dioxide emissions) varied widely based on location due to prices of natural gas and electricity, source-to-site conversion factors, and carbon dioxide emissions conversion factors for electricity and natural gas. Variations in each system efficiency affected R_{min}, but varying the power generation unit efficiency had the most dramatic effect in the overall savings potential from the proposed system.

1. Introduction

A combined heat and power (CHP) system simultaneously generates on-site electricity and provides useful heat by utilizing waste heat from a power generation unit (PGU) [1]. CHP systems can enhance energy production efficiency and energy sustainability by reducing grid dependency, often yielding cost savings in the process [2]. CHP systems can potentially provide significant savings over separate heating and power (SHP) systems not only in terms of operational cost and primary energy consumption (PEC) [3], but also in terms of carbon dioxide emissions (CDE) [4]. Knizley and Mago [5] have also explored the performance of CHP systems with dual power generation units for various benchmark buildings and determined that CHP system performance can vary widely among different facilities.

An organic Rankine cycle (ORC) can be incorporated into a CHP system to allow for increased potential reductions in operational cost, PEC, and CDE when compared to separate heat and power (SHP) systems [6]. An ORC utilizes an organic working fluid. The evaporation of the organic fluid takes place at a lower temperature than does the evaporation of water in conventional Rankine cycles [7]. The evaporation temperature is a key factor in the efficiency of an ORC because it allows the ORC to recover heat from relatively low-temperature sources [8], such as geothermal heating, biomass combustion systems, solar energy systems [9], and industrial waste heat. ORCs can be a highly efficient method for converting low-grade thermal energy into electricity [8]. As demonstrated by Yamamoto et al. [10], ORCs not only possess a significant advantage over conventional Rankine cycles in terms of energy efficiency, but are also an attractive choice because they do not emit pollutants such as CO, CO_2, or NO_x.

Research has indicated that ORCs can provide considerable economic benefits over more conventional means of recovering waste heat. For example, Heberle and Brüggemann [11] have presented a thermo-economic analysis of the ORC and illustrated its economic advantages, particularly when combined with a geothermal energy source. Law et al. have performed a comparative study between a high-temperature heat pump and an ORC using theoretical models. They found the ORC yielded higher cost savings as well as higher

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Nomenclature

CHP	combined heat and power
ORC	organic rankine cycle
PGU	power generation unit
$E_{pgu-ORC}$	power generated by the PGU–ORC configuration
E_{pgu}	electricity generated by the power generation unit
E_{ORC}	electricity generated by the ORC
E_{HP}	electricity required to operate the heat pump
E_b	electricity required by the building for lights and other equipment except the heat pump.
E_m	total electricity registered at the electric meter
F_{pgu}	fuel energy supplied to the PGU
η_{pgu}	efficiency of the PGU
Q_{pgu}	heat that can be recovered from the PGU
η_{HRS}	efficiency of the heat recovery system
ξ	factor that accounts for PGU energy losses
Q_b	thermal load of the building
COP	heat pump coefficient of performance
$Cost_{pgu-ORC}$	cost to operate the PGU–ORC system
$Cost_f$	cost of the fuel
$Cost_{CV}$	cost to operate the building for the conventional case
$CDE_{pgu-ORC}$	carbon dioxide emissions (CDE) associated with the PGU–ORC system
CDE_f	CDE factor for the system
CDE_{CV}	CDE connected with the conventional case
$PEC_{pgu-ORC}$	primary energy consumption (PEC) for the PGU–ORC system
PEC_f	PEC factor for the system
PEC_{CV}	PEC resulting from operating the building for the conventional case
R_{cost}	cost ratio defined as $Cost_e/Cost_f$
R_{CO_2}	CDE ratio defined as CDE_e/CDE_f
R_{PEC}	PEC ratio defined as PEC_e/PEC_f
R_{min}	minimum R_{cost} that provides cost savings for the PGU–ORC system versus the conventional system
Red_{cost}	cost reduction defined in Eq. (15)
Red_{PEC}	PEC reduction defined in Eq. (16)
Red_{CDE}	CDE reduction defined in Eq. (17)

greenhouse gas reductions. Additionally, they completed a sensitivity analysis based on utility cost trends that suggests the ORC will be much more profitable than the heat pump in future years [12].

Significant theoretical and experimental analysis of the efficiency of ORCs has taken place in recent years. It has been shown by researchers such as Hung [13], Liu et al. [14], and Saleh et al. [15] that the efficiency of operating a given ORC can vary greatly depending on the thermodynamic properties of the working fluid as well as the cycle operating conditions. Hung et al. have investigated numerous refrigerants and examined their effectiveness for recovering low- and high-temperature waste heat [16]. Research has also taken place toward the end of developing an optimum design criterion for ORCs. For example, Hettiarachchi et al. utilize a loss function comprising the ratio of total heat exchanger area to net power output in order to select the optimum working fluid for a given application [17]. Dai et al. explored a parametric optimization of ORC performance based on the thermodynamic properties for various working fluids and verified that cycles with organic working fluids are significantly more efficient for converting waste heat into useable energy than those with water as the working fluid [18].

Additionally, work has been done toward predicting the behavior and potential cost savings of ORCs. Zhang et al. have proposed a generalized predictive control algorithm that outputs a set of variable adjustments to optimize ORC behavior for a given facility [19]. Zhang et al. have also demonstrated the use of a constrained model predictive control (MPC) strategy to enhance the efficiency of ORC systems [20]. Wei et al. have demonstrated the benefits of maximizing the usage of exhaust heat and keeping the degree of cooling at the condenser outlet within an optimal range for the chosen working fluid, as well as examined the negative effects of high ambient temperature on output net power and efficiency [21].

The principal thermal energy source examined in this paper is waste heat from power generation units (PGUs) in both the residential and commercial sectors. In this paper, the authors seek to develop a metric which can be utilized to estimate quickly whether operational cost savings can be achieved from an ORC and how much savings ought to be expected. Additionally, while many predictive strategies rely upon predictive algorithms and location-specific factors such as facility and climate conditions, the tool proposed in this paper relies upon a relatively simple equation and is dependent only on the efficiencies of the system components and local prices of electricity and natural gas, allowing for simpler and more universal application.

2. Analysis

This section presents the model used to evaluate the performance of the proposed PGU–ORC system, shown in Fig. 1, and the conventional system, shown in Fig. 2.

2.1. Combined PGU–ORC

The power generated by the PGU–ORC configuration, $E_{pgu-ORC}$, can be expressed as:

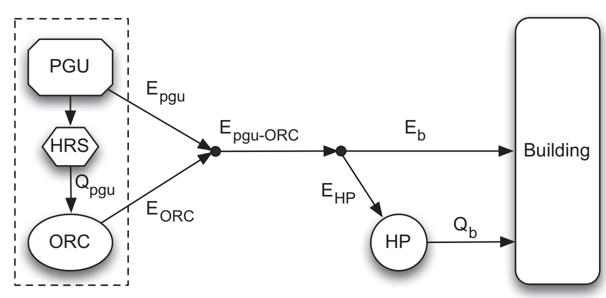

Fig. 1. Schematic of the PGU–ORC model.

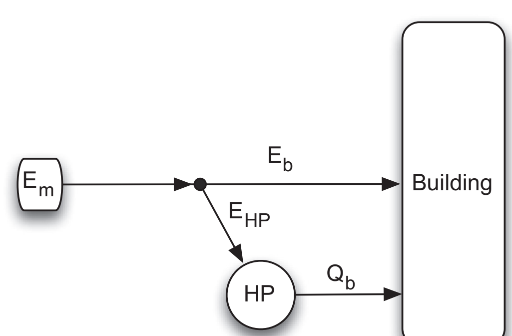

Fig. 2. Schematic for the conventional case.