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Integrating cogeneration and intermittent waste-heat recovery in food processing: Microturbines vs. ORC systems in the coffee roasting industry

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HIGHLIGHTS

- A novel intermittent waste heat recovery system is investigated for coffee roasting processes.
- A real case study of a major coffee roasting firm is proposed.
- A techno-economic comparison of CHP and waste heat recovery configurations is provided.
- Key techno-economic factors influencing investment profitability is proposed.

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ABSTRACT

Coffee roasting is a highly energy intensive process wherein a large quantity of heat is discharged from the stack at medium-to-high temperatures. Much of the heat is released from the afterburner, which is required to remove volatile organic compounds and other pollutants from the flue gases. In this work, intermittent waste-heat recovery via thermal energy storage (TES) and organic Rankine cycles (ORCs) is compared to combined heat and power (CHP) based on micro gas-turbines (MGTs) for a coffee roasting plant. With regard to the former, a promising solution is proposed that involves recovering waste heat from the flue gas stream by partial hot-gas recycling at the rotating drum coffee roaster, and coupling this to a thermal store and an ORC engine for power generation. The two solutions (CHP + MGT prime mover vs. waste-heat recovery + ORC engine) are investigated based on mass and energy balances, and a cost assessment methodology is adopted to compare the profitability of three system configurations integrated into the selected roasting process. The case study involves a major Italian roasting plant with a 3,000 kg per hour coffee production capacity. Three options are investigated: (i) intermittent waste-heat recovery from the hot flue-gases with an ORC engine coupled to a TES system; (ii) regenerative topping MGT coupled to the existing modulating gas burner to generate hot air for the roasting process; and (iii) non-regenerative topping MGT with direct recovery of the turbine outlet air for the roasting process. The results show that the profitability of these investments is highly influenced by the natural gas and electricity prices and by the coffee roasting production capacity. The CHP solution via an MGT appears as a more profitable option than waste-heat recovery via an ORC engine primarily due to the intermittency of the heat-source availability and the high electricity cost relative to the cost of natural gas.

1. Introduction

Waste heat recovery in industry is a topic of great importance and has been attracting growing interest from diverse stakeholders [1]. In particular, the food processing sector is a highly energy-intensive industry, which makes up 7% of total EU energy consumption [2], with around 57% of the primary energy input being lost as waste heat during the production [3]. Several investigations have been performed with the aim of improving the efficiency of food production, including heat and power cogeneration cycles [4] and waste heat recovery systems [5]. Some studies propose waste heat recovery for drying or preheating food products [6], or for other purposes such as space or district heating [7]. When the waste-heat stream has a sufficient temperature level, it can be used for power generation via mature technologies such as the

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Nomenclature

Abbreviations

CHP	combined heat and power
LHV	lower heating value
MGT	micro gas-turbine
NG	natural gas
ORC	organic Rankine cycle
PM	particulate matter
TES	thermal energy storage
VOCs	volatile organic compounds

Variables

$c_{p,hr}$	specific heat capacity of pressurized water in TES (J/kg K)
η_{ORC}	thermal efficiency of ORC engine (%)
h_E	ORC and MGT plant operating hours (h/year)
h_{drum}	enthalpy of flue gas in drum (J/kg)
h_{in}	enthalpy of flue gas at MGT outlet (J/kg)
$\dot{m}$	gas turbine mass flow rate (kg/s)
m_{hr}	mass of water in the TES (kg)
$\dot{m}_{hr}$	mass flow rate of water in TES (kg/s)
P_{cond}	ORC working fluid condensation pressure (Pa, bar)
P_{evap}	ORC working fluid evaporation pressure (Pa, bar)
P_E	electric power output from MGT and ORC (W)
$\dot{Q}$	thermal power recovered from cycle (W)
$\dot{Q}_{hr}$	intermittent rate of heat transfer from flue gases to TES (W)
$\dot{Q}_{ORC}$	constant heat transfer rate from pressurized water to ORC (W)
T_{hr}	temperature of the pressurized water in the TES (°C)
$T_{hr,sup}$	supply temperature of water in TES (K, °C)
$T_{hr,ret}$	return temperature of water in TES (K, °C)
$\dot{W}_{ORC}$	net power output from ORC engine (W)

Kalina cycle [8], or the organic Rankine cycle [1,9,10], or even earlier-stage technologies currently under development such as thermoacustic [11] or thermofluidic heat engines [12]. In particular, the Non-Inertive-Feedback Thermofuidic Engine (NIFTE) [13,14] and the Up-THERM heat converter [15,16] have been shown to be competitive with established technologies, such as ORCs [17], due to their small number of moving parts, and low capital and running costs. Nevertheless, ORC technology is more established, commercially available and has been selected for the present study.

Intermittent heat recovery applications can be included, such as sintering processes [18], or furnaces in steel manufacturing [19] and combined cycles where cogenerated heat from onsite power production is combined to waste heat streams [20], with the possibility to adopt multi-fuel energy sources [21]. Most of the heat recovery studies have been focused so far on continuous processes, with limited attention to recovering waste heat from batch processes [22]. However, around 50% of industrial food processes use batch processes, which are typically needed to improve the quality and consistency of the product [23] such as coffee roasting [24], dairy pasteurization [25] and alcoholic beverage production [26]. The drawback of batch processes is the substantial amount of waste heat emitted intermittently and at variable temperature level, preventing conventional heat recovery methods from being used. Waste heat recovery from batch processes in industrial and food processing sectors have been investigated in the literature implementing heat integration approaches [27], optimising the plant layout [28] and improving the efficiency of the process through heat stream analyses [29]. Heat integration can be either direct or indirect [30], the latter requiring a thermal energy storage (TES) system [31]. TES systems have been shown to be the most successful for recovering waste heat in industrial batch plants [32], including food processing applications and multipurpose batch plants [33].

The present work considers a techno-economic analysis of a waste-heat recovery system for an intermittent coffee-roasting process based on the integration of a TES system with an ORC plant. The novelty of this study is in the optimization of the ORC engine for steady-state operation, considering different working fluids and temperature levels, and in the decoupling of the operation of the ORC plant from the intermittent waste-heat source supply via proper sizing of the TES. The profitability of the proposed solution is verified with respect to standard alternative solutions based on the use of natural-gas-fired (NG) cogenerative micro gas-turbines (MGTs).

The case study of a major coffee processing plant with a 3000 kg/h production capacity and the Italian electricity/(NG) cost scenario are used for the techno-economic assessment. Three technical solutions for increasing the efficiency and reducing the energy costs of the coffee roasting process are considered: (1) intermittent waste-heat recovery from the hot flue-gases through an ORC engine coupled to TES; (2) regenerative MGT coupled to the existing modulating gas burner to generate hot air for the roasting process and electricity to match electric demand of the process; (3) non-regenerative MGT with direct recovery of turbine outlet air for the roasting process by means of an afterburner that modulates the heat demand of the roasting process. The investment profitability sensitivity to the main techno-economic process parameters (i.e. daily roasting operating hours and avoided cost of electricity) is discussed.

The relevance of the research relies in comparing different energy saving strategies integrated in the coffee production process in presence of intermittent waste heat source, and in identifying the key factors that influence their relative profitability. The conclusions and insights from this work are transferable to other batch food production processes. The coffee roasting process features and thermal storage options are introduced in Sections 2 and 3, while Section 4 presents the methodology, Section 5 describes the application to the three case studies, Section 6 reports the techno-economic input data and cost-benefit analysis, and finally Section 7 proposes a comparison of the investment profitability and a sensitivity analysis based on different CHP sizes. The results show that the profitability of these investments is highly influenced by the natural gas and electricity cost and by the coffee roasting production capacity.

2. Coffee roasting process

Coffee roasting is a unique source of intermittent waste heat due to the relatively high temperature of the exhaust gas and the typical cyclic process. The coffee roasting industry is a growing food processing segment with 6.7 billion kg of coffee being roasted every year [34]. It requires 11.2×10^{12} kJ of input energy annually, with 75% of the energy being wasted as heat through the stack [35]. A big challenge for roasting is to rapidly heat the air before introducing it into the batch. To achieve this rapid heating, the roasters use a very energy intensive and quite inefficient process.

Coffee roasting is a process that converts green coffee beans into beans that can be ground, brewed and consumed with a complex aroma and flavour. Coffee roasting technologies come in several different configurations with batch roasters and continuous roasters the most common [36]. Continuous coffee roasters involve a conveyor belt that slowly moves the beans through the furnace, roasting them continuously and in large quantity. Batch coffee roasters operate in batches and allow higher process uniformity and quality of the beans. The operation of batch gas-fired coffee roasters equipped with afterburners is