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Optimal sizing and operation of on-site combined heat and power systems for intermittent waste-heat recovery

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Abstract

Coffee roasting is a highly energy intensive process with much of the energy being lost in intermittent cycles as discharged heat from the stack. In this work, combined heat and power (CHP) systems based on micro gas-turbines (MGT) are investigated for providing heat to the roasting process. Much of the heat released in a coffee roaster is from the afterburner that heats up the flue gases to high temperatures in order to remove volatile organic compounds (VOCs) and other pollutants. An interesting solution for utilizing waste heat is assessed through energy and material balances of a rotating drum coffee roasting with partial hot gas recycling. A cost assessment methodology is adopted to compare the profitability of three proposed system configurations integrated into the process. The case study of a major coffee torrefaction plant with 500 kg/h production capacity is assumed to carry out the thermo-economic assessment, under the Italian energy framework. The CHP options under investigation are: (i) regenerative topping MGT coupled to the existing modulating gas burner to generate hot air for the roasting process; (ii) intermittent waste-heat recovery from the hot flue-gases through an organic Rankine cycle (ORC) engine coupled to a thermal storage buffer; and (iii) non-regenerative topping 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 results show that the profitability of these investments is highly influenced by the natural gas/electricity cost ratio, by the coffee torrefaction production capacity and by the intermittency level of discharged heat. The MGT appears as a more profitable option than waste-heat recovery via the ORC engine due to the intermittency of the heat source and the relatively high electricity/heat cost ratio.

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Keywords: coffee torrefaction, intermittent heat recovery, micro gas turbine, organic Rankine cycle, waste heat recovery.

1. Introduction

Coffee roasting is a growing industry with 6.7 billion kg of coffee being roasted every year. It is highly energy intensive, requiring 11.2×10^{12} kJ/fuel energy annually, with 75% of the energy being wasted as heat through the stack [1,2]. Around 50% of industrial processes such as coffee roasting, sintering, dairy production and pharmaceuticals use batch processes to improve the quality and consistency of the products [3-6]. The drawback to batch processes is the substantial amount of waste heat emitted intermittently, preventing conventional methods from being used for recovery. Heat recovery of batch processes across industries has been investigated in the literature to reduce energy use [7-9], and heat storage systems have proven to be successful in recovering wasted heat [10-15].

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The operation of batch gas-fired coffee roasters equipped with afterburners is well known and widely described in literature [16-19]. The methods include a heating air process, generally by means of a modulating gas burner, followed by passing the hot air through the coffee beans passively with a batch process that lasts around 10 minutes. The hot air usually travels from the roasting chamber through an afterburner to remove the VOCs and carbon monoxide and is finally discharged at high temperature into the atmosphere. This single-pass roasting method is often substituted to a semi-closed loop where part of the roaster gases are recycled and mixed to the hot air flow in order to roast the beans with the desired time-temperature curve. 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 low efficiency process. The afterburner is also quite energy intensive and releases the final gas at a very high temperature. In this paper, energy and material balances of a rotating drum coffee roasting with partial hot gas recycling and costs assessment methodologies are adopted to compare the profitability of three cogeneration systems integrated into the process. The case study of a major coffee processing plant with 500 kg/h production capacity and the Italian electricity/natural gas (NG) cost scenario are assumed to carry out the thermo-economic assessment. The CHP options under investigation are: (i) regenerative topping MGT coupled to the existing modulating gas burner to generate hot air for the roasting process; (ii) fluctuating waste-heat recovery from the hot flue-gases through an ORC engine with a thermal storage buffer; and (iii) non-regenerative topping MGT with direct recovery of turbine outlet air for the roasting process by means of afterburner to modulate heat demand of roasting. The sensitivity of investment profitability to the main technoeconomic process parameters and in particular to the daily roasting operating hours and electricity/NG cost ratio is presented.

2. Coffee roasting process description

The coffee roasting process is a chemical process that turns green coffee beans into beans that can be ground, brewed and consumed with a complex aroma and flavor. For a batch coffee roaster, the roasting happens in cycles as the green coffee beans enter the roasting drum and are heated to the desired temperature of 200-250 °C before being transferred to a cooling chamber [20,21]. A cycle lasts 10 to 20 minutes depending on the desired degree of roasting. The roasting drum is a horizontal rotating chamber that rotates at a specified speed to induce mixing without the beans getting stuck to the walls from centrifugal forcing. Hot air is generated in a combustion chamber, usually fueled by NG, and passes through the roasting drum, heating the beans to the desired temperature. The first stage of coffee roasting involves the evaporation of water from the bean when it reaches temperatures between 160 °C and 190 °C [18,22-24]. After water removal, the bean undergoes of set of chemical reactions in pyrolysis, which give the coffee its final flavor and aroma at a temperature of 200-250 °C. During pyrolysis, there is also a release of volatile organic compounds, carbon dioxide, and particulate matter from the roasted chaff that is added to the flue gases in the roasting drum. When too many volatiles are released from the bean at temperature higher than 200 °C, the aroma of the bean can decrease. For this reason, the temperature gradient during the process must be constant in order to achieve a uniform and gradual heating of the beans from the outside to the center. This is done by means of a modulating boiler that can control the output of heat into the roasting drum. Some of the flue-gas flow is returned to the combustion chamber at 180-230 °C through a heat exchanger to utilize some of the waste heat and increase the efficiency of the burner. For the rest of the flue gas leaving the roasting drum, the VOCs, PM and CO_2 must be removed before being emitted to the environment to comply with air quality standards. The flue gases flow through a cyclone to remove particulate and then an afterburner to combust pollutants that are released from the beans during the roasting phase and is then finally released through a chimney into the atmosphere at temperatures of 300-350 °C.

Due to the nature of the batch coffee roasting process, waste heat is released intermittently at the end of each 10-min cycle, over a discharge period of about 15 s. This intermittency prevents a constant flow of mass and energy from which to recover heat and reutilize this in systems such as ORC engines. This can be alleviated by using a thermal storage system, either sensible heat thermal storage or latent heat thermal storage. Sensible heat storage systems are most common and use a medium such as pressurized water to store the generated energy from the intermittent source through a heat exchanger. As the flue-gas flow passes through the heat exchanger, its temperature drops, causing a potential issue of fouling. The VOCs and other compounds in the flue gas could condense on the heat exchanger, lowering the efficiency of the heat transfer. The optimal size of the thermal storage tank must also be determined considering the intermittent heat addition and constant release to the ambient air.

The production site being investigated in this work is a large coffee roasting plant that has roasting capacity of 500 kg/h. The plant operates over 6 hours per day and 1,560 hours per year. There are two torrefaction units that roast 250 kg of beans per cycle with each cycle lasting 10 minutes. The modulating boiler and afterburner are fueled by NG. Each cycle requires 1.5 MJ of natural gas fuel per kg of beans, or 375 MJ per cycle. With the plant operating at 6 hours per day and 5 days a week, it requires 7,020 GJ of natural gas and 800 MWh of electricity per year. The modulating boiler operates in the range 175-940 kW. The temperature of the exhaust gas from the stack is in the range 300-350 °C and the flow rate is 4,500 Nm^3/h. This hot air flow rate is assumed constant through the system. A schematic of the investigated torrefaction process is shown in Fig. 1(left).

3. Scenarios under investigation

The roasting process is carried out at a relatively low temperature, hence it is possible to improve the overall efficiency recovering thermal energy from a topping MGT in cogenerative configuration or recovering the thermal energy content of the flue gases exiting the afterburner section via an ORC engine, as described below.

3.1. Case Study 1: Regenerative CHP-MGT

A possible solution where a topping MGT is installed before the fresh air inlet is reported in Fig. 1(right). Therefore the MGT exhaust gas is mixed with the recirculated stream and driven to the furnace, where the temperature is adjusted by means of the existing burner before entering the roasting drum. Assuming that the roasting process is carried out at average temperature of 200 °C and a typical exhaust gas temperature of a regenerative gas turbine is 270 °C the heat recovered can be calculated from:

$$\dot{Q} = \dot{m}(h_{\text{in}} - h_{\text{drum}}) \tag{1}$$

where $\dot{Q}$ is the heat recovered; $\dot{m}$ is the gas turbine exhaust gas flow rate; h_{in} is the enthalpy of the flue gases at the gas turbine outlet temperature; h_{drum} is the enthalpy of the flue gases at the drum temperature.

Assuming the data of a commercial 200 kWe MGT, with exhaust gas flow rate of 1.3 kg/s and outlet temperature 270 °C, and assuming the flue gas composition in Table 1, the heat recovered Q is 58.3 MJ in a 10-min cycle.

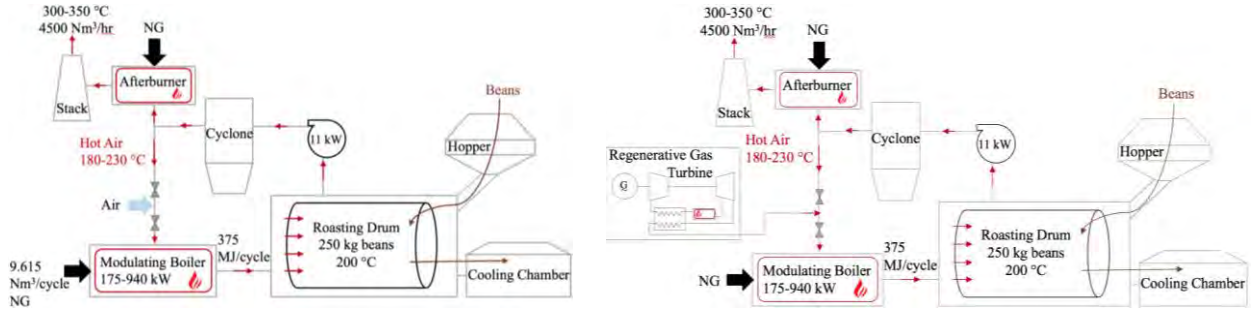


Fig. 1. LEFT – Flow chart of the coffee torrefaction process. RIGHT – Schematic of CHP-MGT in Case Study 1 with electricity from the MGT fed to the grid or consumed onsite and cogenerated heat used for the torrefaction process.

Assuming a heat demand of 1.5 MJ/kg of green beans and a processed mass of 250 kg, the heat required per cycle is 375 MJ. The MGT gas flow rate of about 3,700 Nm^3/h is coherent with the flow rate discharged into atmosphere in a commercial roasting process, which means a minor perturbation to the original process.

Case Study 2: Waste-heat recovery via ORC

Another viable option for the recovery of waste heat from the coffee torrefaction process is via an ORC system. The torrefaction process generally lasts 10 minutes after which the 'torrefied' coffee is extracted and the torrefaction air with coffee peel is discharged to a post burner. In the post burner, the coffee peel is further burnt to avoid emissions of coffee peels and the eventual flue gases exit the afterburner at around 350 °C and at a flowrate that varies linearly

between 2,500 and 4,500 Nm^3/h in 10 min. This variability necessitates a thermal energy storage system (TES) in the form of a pressurized-water loop (it is also possible to use a hot-oil loop here), to recover the discharged heat from the flue gases; the flue-gas flow is then discharged to the environment at a lower temperature of 120 °C. This pressurized-water loop acts as the heat source to the (subcritical and recuperative) ORC system, ensuring a constant availability of heat to the ORC system. The schematic of the coffee torrefaction process with the ORC power system is shown in Fig. 1(right). A temporal energy balance around the heat recovery loop is described in Eq. (2), where T_{hr}, m_{hr} and $c_{\mathrm{p,hr}}$ are the temperature, mass and specific heat capacity of the pressurized-water in the heat recovery loop. $\dot{Q}_{\mathrm{hr}}(t)$ is the (fluctuating) rate of heat transfer from the flue gases to the heat recovery loop; the profile is provided in Fig. 2. $\dot{Q}_{\mathrm{ORC}}$ is the (constant) heat transfer rate from the pressurized-water stream to the ORC working fluid in the ORC evaporator. The thermal storage system is designed (by suitably modifying m_{hr} and $\dot{m}_{\mathrm{hr}}$) such that ~288 kW of heat is constantly supplied to the ORC system during the coffee torrefaction process. In all the heat exchangers, the minimum pinch temperature difference is assumed to be 10 °C.

$$m_{\mathrm{hr}} c_{\mathrm{p,hr}} \frac{\mathrm{d}T_{\mathrm{hr}}}{\mathrm{d}t} = \dot{Q}_{\mathrm{ORC}} + \dot{Q}_{\mathrm{hr}}(t), \text{ where } \dot{Q}_{\mathrm{ORC}} = \dot{m}_{\mathrm{hr}} c_{\mathrm{p,hr}} \left(T_{\mathrm{hr,sup}} - T_{\mathrm{hr,ret}}\right). \tag{2}$$

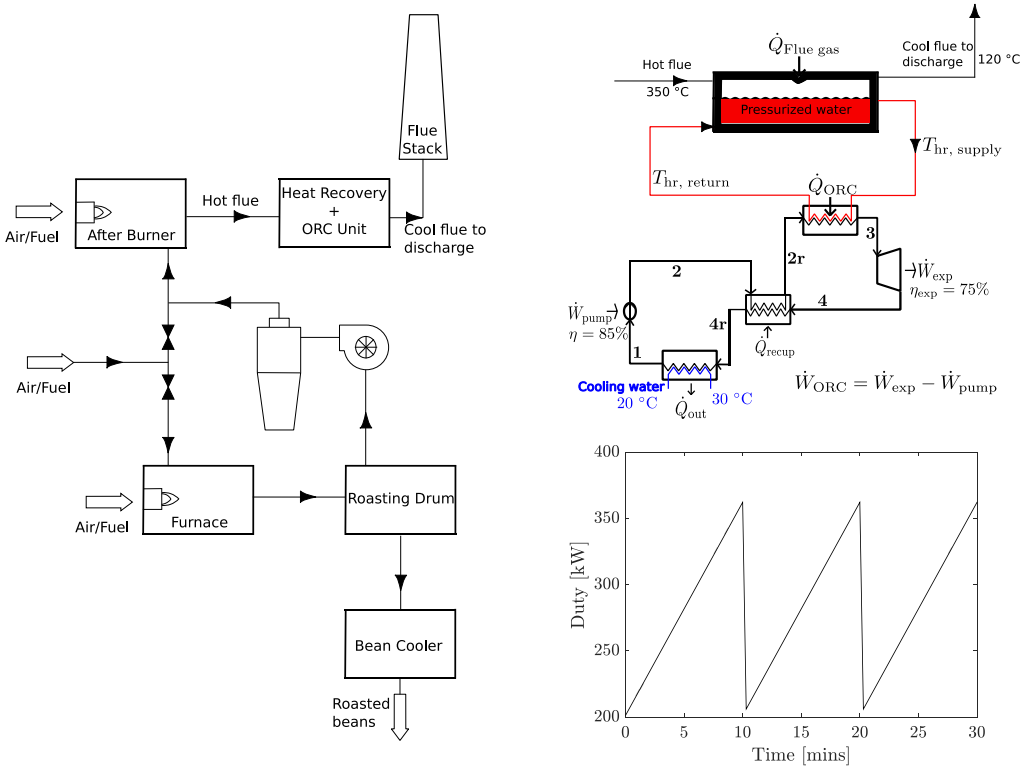


Fig. 2. Case Study 2: Waste-heat recovery from flue gases via the organic Rankine cycle (ORC) system. LEFT – Schematic of coffee torrefaction process showing heat recovery and ORC power generating unit. TOP RIGHT – Schematic of pressurized-water heat recovery unit and recuperative ORC engine. BOTTOM RIGHT – Temporal profile of process flue gases (over three cycles) discharged at 350 °C to the atmosphere.

A few of the common ORC working fluids were also considered here and are listed in Table 1, where the results of maximizing the net power output ($\dot{W}_{\mathrm{ORC}}$) from the ORC system (at $T_{\mathrm{hr,sup}} = 120$ °C and 150 °C) are presented; in both cases, $T_{\mathrm{hr,ret}} = 90$ °C. These temperature ranges are selected to ensure thermal stability of the ORC working fluid. While the same amount of heat (~290 kW) is supplied in both cases, the pressurized water flowrate ($\dot{m}_{\mathrm{hr}}$) in the 150 °C is double that of the 120 °C case. At a supply temperature of 120 °C, the ORC systems delivers in excess of 26 kWe while it delivers over 30 kWe at a supply temperature of 150 °C. This is a result of the higher thermal efficiency of the ORC in the 150 °C case, brought about by the higher average temperature of heat addition. The inclusion of a recuperator in the ORC system is also seen to improve its efficiency as up to 98 kW of heat is 'internally recovered' within the ORC system.

Table 1. Maximum net power output and cycle design conditions of the ORC engine.

	$T_{\mathrm{hr,sup}} = 120$ °C					$T_{\mathrm{hr,sup}} = 150$ °C				
Working fluid	Butane	Pentane	R227ea	R245fa	R1234ze	Butane	Pentane	R227ea	R245fa	R1234ze
$\dot{W}_{\mathrm{ORC}}$ (kW)	26.2	25.9	26.6	26.3	26.3	30.3	29.8	32.3	30.4	33.2
η_{ORC} (%)	9.07	8.99	9.21	9.10	9.13	10.5	10.3	11.2	10.5	11.5
P_{evap} (bar)	11.1	4.0	23.4	8.8	24.5	16.2	5.5	27.8	13.6	34.5
P_{cond} (bar)	3.73	1.14	6.84	2.46	7.52	3.73	1.14	6.84	2.46	7.51
$\dot{Q}_{\mathrm{ORC}}$ (kW)	288	288	288	288	288	288	288	288	288	288
$\dot{Q}_{\mathrm{out}}$ (kW)	262	263	262	262	262	258	259	256	258	255
$\dot{Q}_{\mathrm{recup}}$ (kW)	44.8	43.1	58.3	42.8	31.9	11.9	20.1	98.7	11.6	45.7

3.2. Case 3: Non-regenerative CHP-MGT

In Case 3 a non-regenerative MGT is used. The system considers the replacement of the existing NG modulating burner and the set up of an in-line afterburner in order to guarantee the same performance of the original system, modulating the furnace temperature operating on the afterburner, and allowing at the same time a baseload operation of the MGT. Such a solution is characterized by a higher turbine outlet temperature, but also a higher fuel consumption and lower electric efficiency due to the lack of heat recovery from regeneration. With the unitary cost assumed there is no difference respect to the solution with the regenerative MGT. The choice depends upon the relative cost of natural gas vs electricity. However, the coupling of the non-regenerative solution with the afterburner is more complicated than the regenerative one, requiring additional controls. For this reason, the investment cost savings achieved with the MGT recuperator are almost balanced by the costs for the afterburner.

Table 2. Main energy balance results and technoeconomic data for the proposed case studies referred to a torrefaction cycle time of 10 min.

	Case 1	Case 2	Case 3
Plant size (kWe)	200	26	200
NG saved (Nm^3/cycle)	1.65	-	10.28
Electricity generated (kWh/cycle)	33.33	4.3	33.33
NG consumption (Nm^3/cycle)	11.31	-	19.90
Saving (Eur/cycle)	5.65	0.65	8.96
Total cost (fuel +O&M) (Eur/cycle)	4.75	0.06	8.06
Balance (Eur/cycle)	0.9	0.59	0.9
Investment (Eur)	200,000	120,000	180,000
Payback time (cycles)	222,200	203,400	200,000
Payback time (6 hours per day operation) (years)	23.7	21.7	21.3

4. Profitability and sensitivity analysis

The annual electricity demand of the plant results of about 800 MWh with a total cost of supply of 150 kEur per year and a corresponding avoided cost for onsite generated electricity of 150 Eur/MWh. The NG supply cost is 0.385 Eur/Nm^3 with a LHV of 10.5 kWh/Nm^3. O&M costs for all cases are assumed of 12 Eur/MWh of electricity generated. On the basis of the energy performance and investment/operational costs, a preliminary cost/benefit analysis is presented. Investment costs are assumed from manufacturers of MGTs [25] and small-scale ORCs [26].

Table 2 reports the electricity output in each 10-min cycle and the correspondent NG consumption and savings for the three case studies. On the basis of fuel costs, O&M costs and investment costs, the economic balances are reported in Table 2, assuming the torrefaction capacity rate of the plant being investigated (36 cycles per day and

9,360 cycles per year). It can be seen from this table that the relatively low production capacity of the proposed case study, and with the assumed electricity and NG costs, the investment profitability is quite low. The results assume that the CHP plant operates only during the coffee torrefaction process to avoid discharged heat from cogeneration. The investment profitability increases when operating the CHP plant baseload and in net metering to the grid, in order to produce, on a yearly basis, the same amount of electricity consumed by the plant.

With the assumed hypothesis, the highest profitability for Case Study 1 is achieved when the CHP electricity output on a yearly basis equals the onsite electricity demand of the plant. In order to evaluate the influence of the electricity/natural gas cost ratio and of the torrefaction production capacity (and consequently heat demand for the process), a sensitivity of investment profitability of the Case 1 (MGT in CHP mode) is proposed in Fig. 3. The two sizes of 100 and 200 kW are compared (with 8,000 and 4,000 operating hours per year, respectively) at different heat demand intensity (which correspond to different production capacity intensity rates, and different cycles per year). As can be seen, at high electricity/natural gas cost ratio and high production capacity intensity, the profitability of the investment increases, and the small scale MGT appears more profitable since it can better match the electricity demand of the plant operating for 8,000 h/a† baseload instead of 4,000 h/a of the 200 kW size CHP. In the same figure, the sensitivity of investment profitability for Case 2 (ORC) is reported, as a function of the torrefaction production capacity (respectively 6.12 and 18 working hours/day) and avoided cost of electricity, and for the 26 kWe ORC size. As can be seen, when increasing the operating hours of the MGT (Case 1), the investment profitability increases and exceeds the one of the ORC, which is highly influenced by the production capacity.

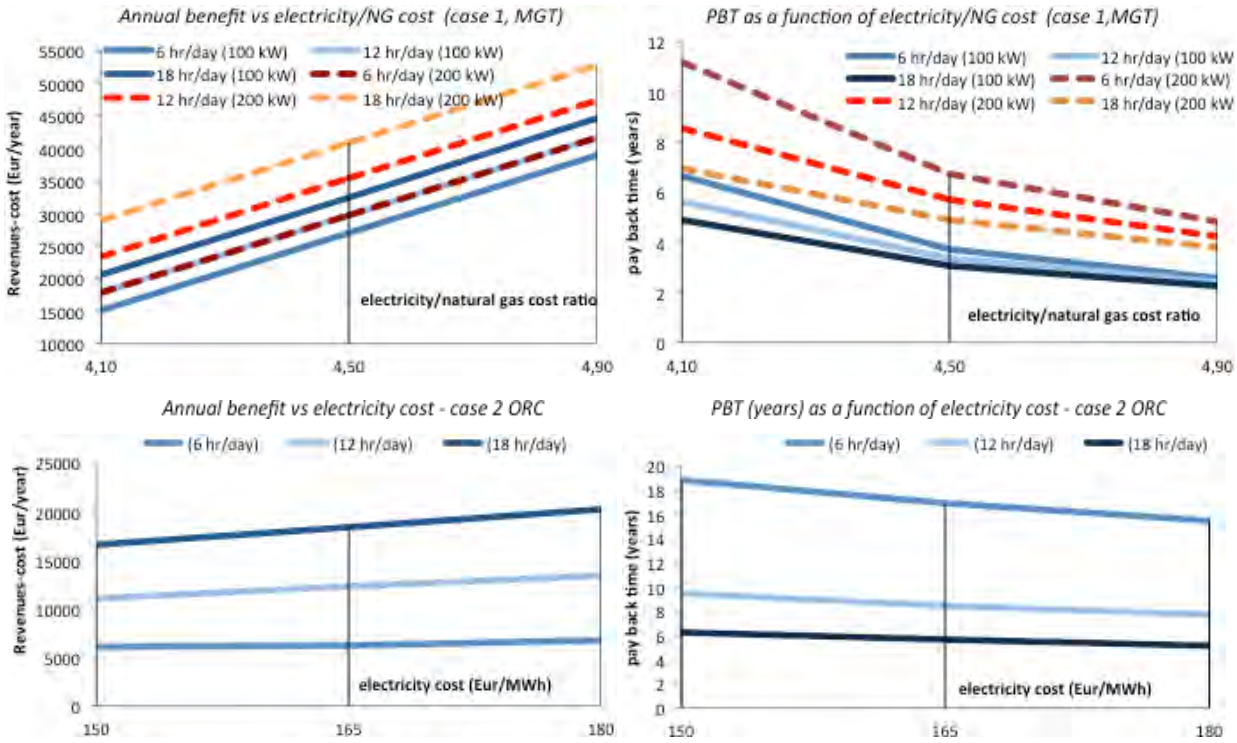


Fig. 3. TOP – Profitability analysis results for Case Study 1 (as a function of electricity/NG cost and CHP size (100 and 200 kW, respectively); the CHP operates baseload at 8,000-4,000 h/a† (100-200 kW size) and the heat demand is varied (1000, 2000, 3000 h/a). BOTTOM – profitability analysis results for Case Study 2 (as a function of electricity cost and process working hours (h/d†) and ORC size (26 kWe).

† h/a: hours per year; h/d: hours per day (SI)

5. Conclusions

In this paper, a rotating drum coffee roasting process with partial hot gas recycling has been assessed and costs assessment methodologies have been adopted to compare the profitability of three cogeneration systems integrated into the torrefaction process. A case study of a major coffee processing plant with a production capacity of 500 kg/h has been used to perform a thermoeconomic assessment. The investigated CHP options are: (i) regenerative topping micro gas-turbine (MGT) coupled to the existing modulating gas burner to generate hot air for the roasting process and electricity for onsite consumption; (ii) fluctuating waste-heat recovery from the hot flue gases via thermal energy storage (TES) and conversion to electricity by an organic Rankine cycle (ORC) engine; and (iii) non-regenerative topping MGT with direct recovery of the turbine outlet air for the roasting process by means of an afterburner thus modulating the heat demand of the roasting process. MGTs are the typical choice for implementing CHP systems in these types of roasters, therefore, ORCs were investigated to determine their feasibility for utilizing more waste heat from the afterburner. The results report a payback time from the ORC solutions ranging between 5 and 6 years for a high production capacity (18 hours per day) and 15 to 18 years if the production capacity is low (6 hours per day). On the contrary, a benchmarking investment in a regenerative MGT operated baseload and in net metering to cover annual onsite electricity demand presents a payback time in the range of 2 to 6 years (according to the electricity/natural gas cost ratio) and is more independent of the torrefaction production capacity. It can be concluded that, with the assumed hypotheses, the onsite CHP via MGTs (Cases 1 and 3) is more profitable than the heat recovery via ORCs (Case 2) whatever the production capacity level and the electricity/gas cost, and the relative profitability is strongly influenced by the electricity/gas cost ratio and heat demand intensity.

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Nomenclature

Symbols	
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
$\dot{Q}$	thermal power recovered from cycle (W)
$\dot{m}$	gas turbine mass flow rate (kg/s)
h_{drum}	enthalpy of flue gas in drum (J/kg)
h_{in}	enthalpy of flue gas at MGT outlet (J/kg)
T_{hr}	temperature of the pressurized water in the TES (°C)
m_{hr}	mass of water in the TES (kg)
$\dot{m}_{\mathrm{hr}}$	mass flow rate of water in TES (kg/s)
$c_{\mathrm{p,hr}}$	specific heat capacity of pressurized water in TES (J/kg K)
$\dot{Q}_{\mathrm{hr}}$	intermittent rate of heat transfer from flue gases to TES (W)
$\dot{Q}_{\mathrm{ORC}}$	constant heat transfer rate from pressurized water to ORC (W)
$T_{\mathrm{hr,sup}}$	supply temperature of water in TES (K, °C)
$T_{\mathrm{hr,ret}}$	return temperature of water in TES (K, °C)
$\dot{W}_{\mathrm{ORC}}$	net power output from ORC system (W)
η_{ORC}	efficiency of ORC working fluid (%)
P_{evap}	ORC working fluid evaporator limits (Pa, bar)
P_{cond}	ORC working fluid condenser limits (Pa, bar)