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## Intermittent waste heat recovery: Investment profitability of ORC cogeneration for batch, gas-fired coffee roasting

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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. CHP systems have been investigated to provide heat to the roasting process by a micro gas turbine (MGT). However, much of the heat released in a coffee roaster is from the afterburner that heats up the flue gas to higher temperatures to remove volatile organic compounds and other pollutants. In this paper, a solution to utilising 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 systems configurations integrated into the process. The case study of a major coffee torrefaction firm with 500 kg/hr 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 micro gas turbine (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 gas through an organic Rankine cycle (ORC) coupled to a thermal storage buffer. 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 intermittency level of discharged heat. MGT seems to be more profitable than waste heat recovery via ORC due to the intermittency of the heat source and the relatively high electricity/heat cost ratio.

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*Keywords:* ORC, waste heat recovery, micro gas turbine, intermittent heat recovery, coffee torrefaction

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## Nomenclature

### Symbols

VOCs	volatile organic compounds
NG	natural gas
CHP	combined heat and power
MGT	micro gas turbine
ORC	organic Rankine cycle
PM	particulate matter
TES	Thermal Energy Storage
$\dot{Q}$	thermal power recovered from cycle (kJ/s)
$\dot{m}$	gas turbine mass flow rate (kg/s)
$h_{drum}$	enthalpy of flue gas in drum (kJ/kg)
$h_{in}$	enthalpy of flue gas at MGT outlet (kJ/kg)
R	heat capacity of flue gas (J/kg K)
$\rho$	density of flue gas (kg/Nm <sup>3</sup> )
$T_{hr}$	T pressurised water in the TES (°C)
$m_{hr}$	mass of water in the TES (kg)

$\dot{m}_{hr}$	mass flow rate of water in TES (kg/s)
$c_{p,hr}$	specific heat capacity of pressurised water in TES (J/kg°C)
$\dot{Q}_{hr}$	intermittent rate of heat transfer from flue gas to TES (kJ/s)
$\dot{Q}_{ORC}$	constant heat transfer rate from pressurised water to ORC (kJ/s)
$T_{hr,supply}$	supply temperature of water in TES (°C)
$T_{hr,return}$	return temperature of water in TES (°C)
$\dot{W}_{ORC}$	net power output from ORC system (kW)
$\eta_{ORC}$	efficiency of ORC working fluid (%)
$P_{evap}$	ORC working fluid evaporator limits (bar)
$P_{cond}$	ORC working fluid condenser limits (bar)
LHV	lower heating value

## 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  $11.2 \times 10^{12}$  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 integration of batch processes across industries have been investigated in the literature to reduce energy use [7-9]. Heat storage systems have proven to be successful in recovering and reusing the heat as seen in further investigations [10-15].

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 firm with 500 kg/hr production capacity and the Italian electricity/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 gas through an ORC with a thermal storage buffer; (. MGTs are the typical choice for implementing CHP systems in these types of roasters, therefore ORCs are investigated to determine their feasibility of utilising more waste heat from the afterburner. The sensitivity of investment profitability to the main techno-economic process parameters and in particular to the daily roasting operating hours and electricity/NG cost ratio is presented, to derive useful insights about the key factors influencing the feasibility of such investments for coffee roasting firms.

## 2. The coffee roasting process under investigation

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 a 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 are added to the flue gas 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 and the resulting product becomes bitter and undesirable. 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. The beans are then sprayed with water which turns to steam upon heat absorption, halting the roasting process of the beans. They are then transferred to a cooling chamber where they are continuously stirred as cool air is blown on them to bring their temperature down to ambient air conditions. Some of the flue gas 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 gases leaving the roasting drum, the VOCs, PM and CO<sub>2</sub> must be removed before being emitted to the environment to comply with air quality standards. The flue gas goes 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 between 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, with a discharge duration of about 15 seconds. This intermittency prevents a constant flow of energy to recover and reuse in systems such as an ORC. This can be done 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 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 is a large coffee roasting firm that has roasting capacity of 500kg/hr. The firm operates 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 firm operating at 6 hours per day and 5 days a week, it requires 7020 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 4500 Nm<sup>3</sup>/hr. This hot air flow rate is assumed constant through the system. A flow chart of the proposed torrefaction process is shown in Fig 1.

## 3. The 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 gas exiting the afterburner section via an ORC, as described in the following.

### 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. 2. 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:

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

where  $Q$  is the heat recovered;  $\dot{m}$  is the gas turbine exhaust gas flow rate;  $h_{in}$  is the enthalpy of the flue gas at the gas turbine outlet temperature;  $h_{drum}$  is the enthalpy of the flue gas 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 of Table 1, the heat recovered  $Q$  is 58.32 MJ in a 10 min cycle.

Assuming a heat demand of 1.5 MJ/kg of green beans and a processed mass of 250 kg, the overall heat required per cycle is 375 MJ. The MGT gas flow rate of about 3700 Nm<sup>3</sup>/h is coherent with the flow rate discharged into atmosphere in a commercial roasting process, which means a minor perturbation to the original process.

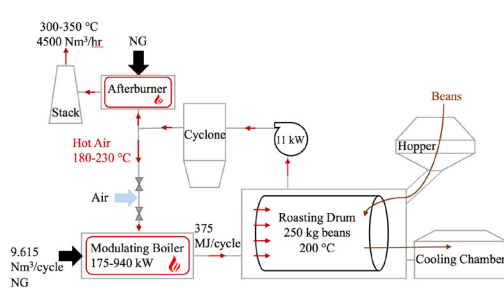


Fig. 1. Flow chart of the coffee torrefaction process.

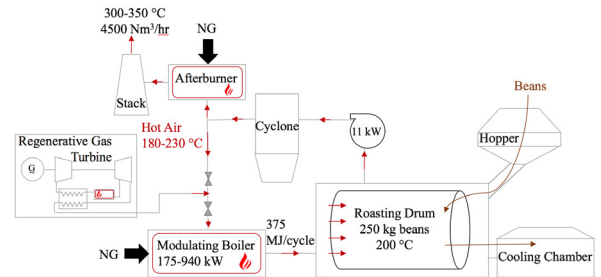


Fig. 2. Schematic of CHP-MGT in Case Study 1: Electricity from the MGT is fed to the grid or on site consumed and cogenerated heat is used for torrefaction process.

### 3.2. 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 gas exits the after-burner at around 350 °C and at a flowrate of 4,500 Nm<sup>3</sup>/h; the flue gas is discharged for a duration of about 15 seconds. Due to the intermittent nature of the flue gas discharge, 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) is employed to recover the discharged heat from the flue gas; the flue gas is then discharged to the environment at a lower temperature of 120 °C. This pressurized-water loop acts as the heat source to the 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. 3. A temporal energy balance around the heat recovery loop is described in Eqns (2) and (3), where  $T_{hr}$ ,  $m_{hr}$  and  $c_{p,hr}$  are the temperature, mass and specific heat capacity of the pressurized-water in the heat recovery loop and  $\dot{Q}_{hr}(t)$  is the (intermittent) rate of heat transfer from the flue gas to the heat recovery loop.  $\dot{Q}_{ORC}$  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  $\dot{m}_{hr}$ ) such that the constant temperatures of the pressurized water are  $T_{hr,supply} = 120$  °C and  $T_{hr,return} = 90$  °C, and supplying ~350 kW to the ORC.. The ORC system configuration is shown in Fig. 4; the system features an extra heat exchanger (the recuperator) to improve its thermal efficiency and power output. In all the heat exchangers, the minimum pinch temperature difference is assumed to be 10 °C, with all cycle processes assumed to be taking place at subcritical pressures due to the low heat source temperature.

Table 1. Composition of flue gas (mass %)

Composition	From MG	From torrefaction
CO2	2.89%	12.58%
H2O	3.56%	2.99%
N2	73.71%	71.08%
O2	18.55%	3.64%
AR	1.29%	1.25%
R [J/kgK]	318.49	291.54
ρo [kg/Nm3]	1,15	1,26

$$m_{hr}c_{p,hr} \frac{dT_{hr}}{dt} = \dot{m}_{hr}c_{p,hr}(T_{hr,return} - T_{hr,supply}) + \dot{Q}_{hr}(t) \quad (2)$$

$$\dot{Q}_{ORC} = \dot{m}_{hr}c_{p,hr}(T_{hr,supply} - T_{hr,return}) \quad (3)$$

The ORC heat sink is assumed to be cooling water supplied at a temperature of 20 °C and discharged at a temperature of 30 °C while the isentropic efficiencies of the pump and expander are assumed to be 85% and 75% respectively. A few of the common ORC working fluids were compared, and at a supply temperature of 120 °C, the ORC systems delivers in excess of 32 kWe while it delivers around 75 kWe at a supply temperature of 150 °C. However, as the input energy to the TES (and hence to the ORC) is fixed and dependent on the intermittency of hot flue gas discharge during the torrefaction process, increasing  $T_{hr,supply}$  from 120°C to 150°C and consequently the TES size from 350 kWt to 700 kWt and the ORC size from 32 to 75 kWe reduces correspondently the operating hours and increases the investment cost (both the expander and the heat exchanger sizes are doubled), while the electric energy output remains quite constant.

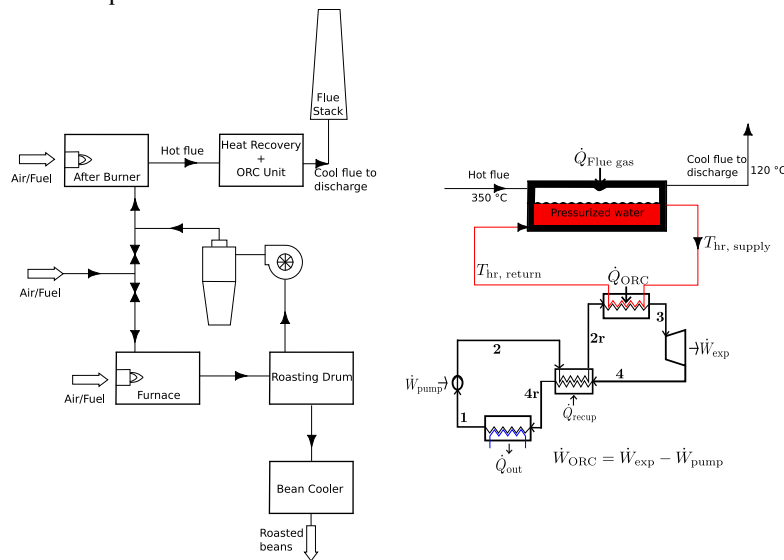


Fig. 3. Case Study 2: Waste heat recovery form flue gas via the organic Rankine cycle (ORC) system: LEFT – Schematic of coffee torrefaction process showing heat recovery and ORC power generating unit; RIGHT – Schematic of pressurized-water heat recovery and recuperative ORC

For this reason, even though the conversion efficiency and maximum power output are higher for the case with a supply temperature of 150°C, it appears clear that the most profitable option is the one that minimizes the installed ORC size and hence the investment cost, i.e., the 120°C supply temperature case. Hence in the profitability analysis, the scenario of 120°C supply temperature and ~30 kWe is taken. The option of larger ORC could be however of interest if a further (and low cost) heat source is available, to integrate the intermittent heat stream fed to the TES, in order to increase the capacity factor of the ORC. The inclusion of a recuperator in the ORC system is also seen to improve its efficiency as up to 200 kW of heat is ‘internally recovered’ within the ORC system.

#### 4. Profitability and sensitivity analysis

The annual electricity demand of the firm results of about 800 MWh with a total cost of supply of 150 kEur/year and a correspondent avoided cost for on site generated electricity of 150 Eur/MWh. The NG supply cost is 0.385 Eur/Nm<sup>3</sup> with a LHV of 10.46 kWh/Nm<sup>3</sup>. O&M costs for all cases are assumed of 12 Eur/MWh of electricity generated. With these assumptions, and on the basis of the energy performance and investment/operational costs of each case study, a preliminary cost/benefit analysis is presented. Investment costs are assumed from manufacturers of MGT [14] and small scale ORC [15]. 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 3, assuming the torrefaction capacity rate of the firm under investigation (36 cycles per day and 9,360 cycles per year). As can be seen, at 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. This operation influences the investment profitability, that 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 firm. With the assumed hypothesis, the highest profitability for case study 1 is achieved when the CHP electricity output on a yearly basis equals the on site electricity demand of the firm. 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 Figure 4. The two sizes of 100 and 200 kW are compared (with operating hours of 8000 and 4000 h/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 firm operating for 8,000 hr/year baseload instead of 4,000 hr/year 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 two ORC sizes of 30 and 75 kW. 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.

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

Table 3. Main economic input data and results for the proposed case studies referred to a torrefaction cycle time of 10 min.

	Case 1	Case 2		Case 1	Case 2
Plant size kWe	200	30	Saving Eur/cycle	5.65	0.75
NG saved Nm <sup>3</sup> /cycle	1.65	-	Fuel Cost Eur/cycle	4.35	-
Electricity generated kWh/cycle	33.33	5	O&M Cost Eur/cycle	0.4	0.06
NG consumption Nm <sup>3</sup> /cycle	11.31	-	total Cost Eur/cycle	4.75	0.06
			Balance Eur/cycle	0.9	0.69
			Investment (Eur)	200,000	120,000
			Pay back cycles	222,222	173,913
			Pay back time (years) (6 hr/day operation)	23.7	18.6

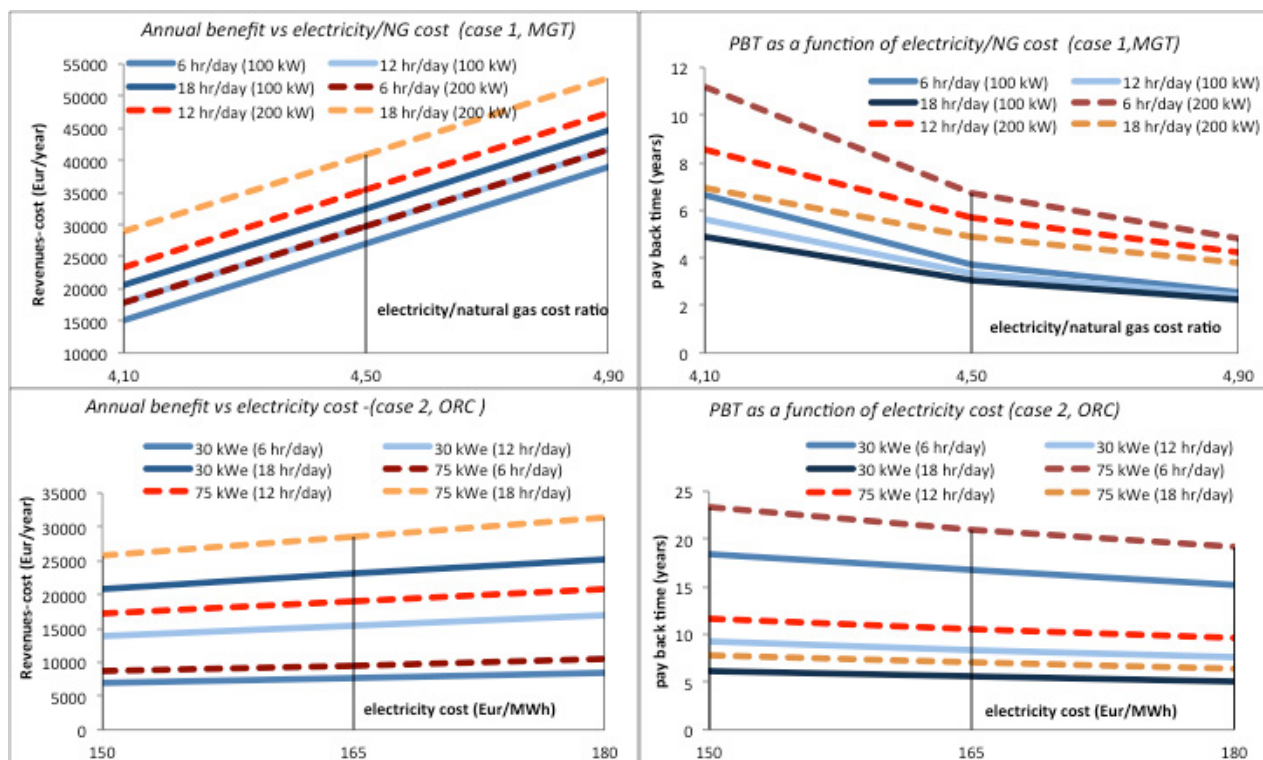


Fig. 4. Top: Profitability analysis results for Case Study 1 (as a function of electricity/NG cost and CHP size (100 and 200 kW respectively); the CHP operates baseload at 8,000–4,000 hours/year (100–200 kW size) and the heat demand is varied (1000, 2000, 3000 hr/year). Bottom: profitability analysis results for Case Study 2 (as a function of electricity cost, proces working hours (hr/day) and ORC size (30 and 75 kWe r)

#### 4. Conclusions

In this paper, energy 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 torrefaction process. The case study of a major coffee processing firm with 500 kg/hr production capacity is 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 and electricity for on site consumption; (ii) fluctuating waste heat recovery from the hot flue gas via a TES and organic Rankine cycle (ORC). MGTs are the typical choice for implementing CHP systems in these types of roasters, therefore ORCs are investigated to determine their feasibility of utilising more waste heat form the afterburner. The techno-economic results report a PBT for ORC ranging between 5 and 6 years in case of high production capacity (18 hr/day) and 15 to 18 years if the production capacity is low (6 hr/day). On the contrary, the benchmarking investment in a regenerative MGT operated baseload and in net metering to cover annual on site electricity demand presents a PBT in the range of 2 to 6 years (according to the electricity/NG cost ratio) and is more independent from the torrefaction production capacity. It can be concluded that, with the assumed hypotheses, the on site CHP via MGT (case 1) is more profitable than the heat recovery via ORC (case 2) whatever the production capacity level and the electricity/NG cost, and the relative profitability is strongly influenced by the electricity/gas cost ratio and heat demand intensity.

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