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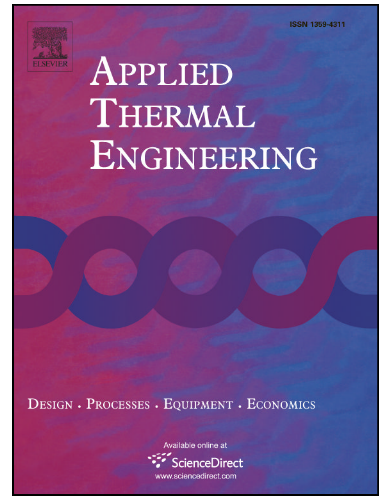

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SPENT COFFEE GROUNDS AS HEAT SOURCE FOR COFFEE ROASTING PLANTS: EXPERIMENTAL VALIDATION AND CASE STUDY

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ABSTRACT

The aim of this work is to validate a new sustainable economic circle where coffee roasting companies recycle spent coffee grounds as a source of thermal energy to produce roasted coffee. The green coffee beans need a significant quantity of heat in the roasting process and this energy could be obtained from the spent coffee grounds ~~(SCG)~~ discarded by espresso bars. According to the concept of circular economy, a coffee company collects the coffee disposed by the bars where it was brewed, and uses it in a heat generator for the roasting process. This paper presents the feasibility of SCG-wood sawdust pelletization and combustion in a 29 kW_{th} air furnace. Results of the tests report a thermal efficiency of 41.2% instead of 37.7% obtained with only wood pellet. In addition, the case study of a small Italian roasting company is discussed. The company produces about 5 tons of roasted coffee per day and it uses 400 Nm^3/day of natural gas as heat source. The company totally satisfies its energy demand through wood-coffee pellet combustion instead of natural gas. According to the business plan, the pay-back period of the investment is four years after which company CO_2 emissions significantly decrease.

Keywords: combustion, coffee, circular economy, thermal valorisation, case study.

1. INTRODUCTION

Industrial energy demand represents an enormous percentage in the world energy panorama: production plants consume about 50% of the world's energy supply [1]. In 2015, Italian production plants consumed more than 25 billion of toe, emitting millions of tons of CO_2 into the atmosphere and the food factories use about 1661 ktoe of energy [2-4]. Both the high cost and the use of fossil fuels constitute a big issue that can be solved thanks to the exploitation of renewable resources like biomass for energy production in a circular economy context [5].

In particular, coffee companies need a large amount of heat to convert green coffee beans to brown roasted coffee beans ready for the brewing process. Coffee is the second biggest traded commodity after petroleum and Italy has a very diffused and appreciated culture in coffee brewing: in the Italian territory, there are hundreds of coffee roasting companies and the province of Modena has a high density of coffee production plants [6]. In the largest majority of the cases, these companies use fossil fuels, like natural gas, to produce the required heat for the roasting. Although natural gas is a good fuel, during the combustion, a substantial quantity of VOCs is generated [7, 8]. The roasted coffee is then directly delivered and sold to the clients, mostly bars, where it becomes espresso and SCG (spent coffee ground). According to the ICO (International Coffee Organization), in 2015 in Italy, the consumption of coffee exceeded the large number of 340000 tons of roasted beans [9]. Therefore, almost the same amount represents the limit for the Italian market in terms of SCG that could potentially be converted into energy.

Today in Italy, SCG are treated as waste and, depending on the local administration, they end up in the undifferentiated garbage or in the organic fraction of municipal waste [10]. In the first case, SCG will end up in an incinerator plant, while in the second case the coffee is directly sent to a composting process. On the other hand, a literature review outlines several ways to use this waste better. Numerous studies promote re-use of SCG in a non-energetic way: from geopolymers, to adsorption of pollutants for water treatments, to the aid of mushrooms growing, to ruminant feed [11-14]. All those reutilizations are interesting but there is no energy exploitation and they are all niche uses. Another utilization considers the use of SCG for agricultural soil, but it can be dangerous for the plant growth [15].

On the other hand, in 2008 Kondamudi et al. [16] proposed an energy re-use of SCG, through oil extraction and making pellets from the SCG. The oil derived from the SCG and the solid residue after extraction can be used to produce biodiesel and electrical energy using the system proposed by Allesina et al. [17]. In addition, the solid residue can be pelletized in order to use it as a more flexible fuel in a downdraft stratified gasifier [18,19]. The two described problems, the energy demand and the disposal of spent coffee, could bring to the community a combined solution: the collection and the reuse of spent coffee grounds in a roasting coffee company that generates heat for the roasting process.

This article introduces a new circular economy model for coffee roasting companies. In the last United Nations Conference on Sustainable Development (UNCSD), also known as Rio+20, the circular economy is presented as a pillar of sustainable development. In addition, some publications show the advantages of the circular economy [20,21]. The model here presented suggests collecting and transforming spent coffee grounds, produced by the clients, into bio-pellets, to satisfy the energy demand of the roasting company. Literature reports several studies about thermal uses of coffee residues [22-24] and a paper concerning waste heat recovery in a coffee roasting plant was presented [25]. However, no studies about integration of these ideas in a coffee company were done. This paper represents a virtuous example of circular economy and it is applied to a case study: the *Caffè Cagliari S.P.A.* [26], a medium-sized coffee roasting company situated in Modena. By analysing the results of experimental combustion tests with different types of pellets made of coffee and pine sawdust, the coffee roasting company can supply its primary energy demand. This transition to a renewable source leads to three main goals: significant savings for the company, reduction of CO_2 emissions in atmosphere and valorisation of a bio-waste.

2. MATERIAL AND METHODS

2.1 Experimental procedure

About 20 kg of spent coffee grounds are collected from three espresso bars in the province of Modena, North of Italy. Once dried, the SCG is mixed with different percentages of pine sawdust locally produced by wood working companies, in order to obtain pellets with a 7.5 kW_{el} pellet mill. The coffee is blended with spruce pine sawdust to increase the mechanical resistance as suggested by Limousy et al. [27]. Three types of pellets are produced: 100% coffee (P_{100}), 70% coffee – 30% sawdust ($P_{70\text{-}30}$) and 50% coffee – 50% sawdust ($P_{50\text{-}50}$). All the quantities are expressed in percentage on dry weight basis. The pellets are then used as fuel in direct combustion tests on a 29 kW_{th} pellet stove.

2.2 Collection and drying process

SCG is collected from bars in the province of Modena. The bar owners have participated actively in the collection, putting the coffee grounds in dedicated bins allowing a good separation of SCG from other waste. Once collected, the coffee is very humid: 45-65% of water content in weight. The drying phase for the 20 kg of coffee consists in spreading it out on a plastic canvas (Figure 1) in a ventilated room for 48 hours with a temperature of 20°C. The colour of the coffee changes to a lighter brown and the consistency becomes dustier. The water content of the naturally dried spent coffee grounds (SDCG) is 7% in weight. Moisture content was evaluated by weighing a sample of coffee before and after the drying process in a Memmert Universal Oven UF30 for 24 hours at 103°C [28, 29].

Figure 1. SCG drying

2.3 Pellet-making and characterisation

The pellets are made with a Cissonius PP-200 pellet mill [30]. The starting materials are SDCG and pine sawdust in different percentages depending the type: P_{100}, $P_{70\text{-}30}$, $P_{50\text{-}50}$ (Figure 2). Also used for the tests is a pure conifer wood pellet, certified EN plus A1, to make a comparison between the optimal fuel for the pellet stove and the coffee-derivative fuel [31]. The water content of the spruce pine sawdust is 8% in weight.

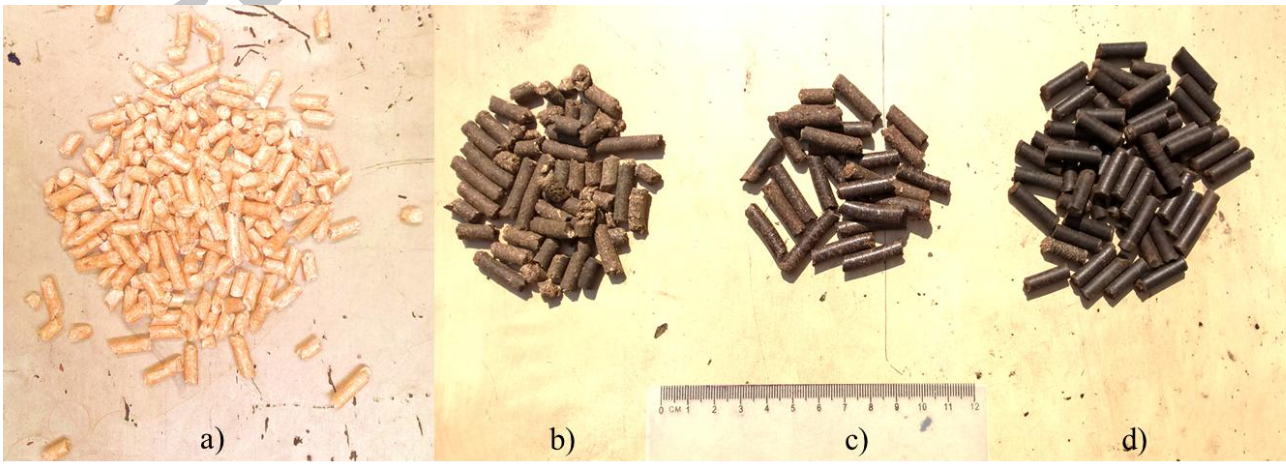

Figure 2. Pellet used as fuel: wood pellet (a), $P_{50\text{-}50}$ (b), $P_{70\text{-}30}$ (c), P_{100} (d).

2.4 Pellets combustion

The pellets are tested in an Ecofaber pellet stove, model AL.PI - GA 35 [32] (Figure 3). The same facility was used to study the combustion of wood-digestate pellets [33]. The combustion chamber is manually fuelled with a known amount of pellets distributed during the test. The stove is a hot air generator exchanging heat between the exhausts and the air that is sucked through a heat exchanger. Then, the exhausts leave the air furnace through a chimney, while the hot air is directed into a pipe where an Extech HD300™ anemometer is placed. This instrument consists of a blade anemometer that measures the velocity in the duct. In the hot air pipe, the air temperature is measured through a K type thermocouple. Others K type thermocouples, connected to a Pico TC-08™ datalogger, are placed in the exhausts chimney, in the combustion chamber and in ambient air. The tests start burning wood pellets for 1 hour while the stove data are monitored. After 1 hour of full load run the temperature stabilizes, then the P_{100}, $P_{70\text{-}30}$ and $P_{50\text{-}50}$ pellets are used as fuel. Each pellet type is tested for about 1 hour. The Higher Heating Value (HHV) of the dry fuel is calculated by Eq. (1), using the elemental composition (Table 1) as defined by Basu [34]:

$$HHV_{dry} = 0.3491C+1.1783H+0.1005S-0.1034O-0.0151N-0.0211ASH \quad (1)$$

Table 1. Elemental composition and HHV_{dry} of SDCG and wood sawdust

Parameter	SDCG	Wood sawdust [35]	$P_{50\text{-}50}$	$P_{70\text{-}30}$
C	48.67 % wt.	46.44 % wt	47.55 % wt	48.00 % wt
H	6.54 % wt	5.10 % wt	5.82 % wt	6.11 % wt
N	2.27 % wt	0.03 % wt	1.15 % wt	1.60 % wt
S	0 % wt	0.10 % wt	0.05 % wt	0.03 % wt
O	40.03 % wt	46.25 % wt	43.14 % wt	41.90 % wt
ASH	2.43 % wt	2.02 % wt	2.22 % wt	2.31 % wt
HHV_{dry}	5.69 kWh/kg	4.83 kWh/kg	5.26 kWh/kg	5.43 kWh/kg

In this paper, the wood sawdust composition refers to Mitchell et al. study [35] where pine sawdust briquettes are used. In such a way the influence of the physical processing on sawdust is considered. $P_{50\text{-}50}$ and $P_{70\text{-}30}$ elemental composition is calculated taking account of SCG and wood sawdust percentages and the calculated HHV_{dry} is then compared with the values illustrated in ECN Phyllis: the results are similar and comparable [36]. The overall efficiency of the air furnace is calculated by Eq. (2):

$$\eta_{tot} = \frac{\rho_{air} c_{p,air} w A \Delta T}{\dot{m}_{pellets,dry} HHV_{dry}} \quad (2)$$

where ρ_{air} = 1.225 [kg m^{-3}] is the density of the ambient air, $c_{p,air}$ =1.005[J kg^{-1} K^{-1}] is the specific heat of the ambient air, w [m/s] in the average air flow velocity, A = 0.023 [m^2] is the section of the outlet duct, ΔT [K] is the air temperature increase from ambient and $\dot{m}_{pellets,dry}$ [kg/h] is the fuel pellets consumption in dry condition.

Figure 3. Pellet combustion facility

3. RESULTS AND DISCUSSION

3.1 Combustion analysis

The combustion tests are made on the Ecofaber 29 kW_{th} pellet stove and the results are summarized in Table 2. The temperature trends in the combustion chamber (red), in the chimney (blue) and in the hot air pipe (green) are shown in Figure 5. Starting from the monitored values of the average hot air flow and the $\Delta T_{hot\ air\text{-}ambient}$, it is possible to calculate the thermal power produced by the stove. Knowing the pellets consumption and their HHV_{dry}, the overall thermal efficiency is calculated. $P_{50\text{-}50}$ performed better in the combustion tests. This is due to the high calorific value of 5.26 kWh/kg and a good thermal power generated of 8.86 kW. These values are greater than that of wood pellet, respectively of 4.83 kWh/kg and 8.02 kW. Calculations suggest that $P_{50\text{-}50}$ leads the highest overall efficiency of 41.2%. Increasing the contents of coffee in the pellets, the problems in combustion raise. In fact, $P_{70\text{-}30}$ and P_{100} caused an unstable combustion. As shown in Figure 4, this is probably due to the significant generation of ash by coffee.

Figure 4. Ash in the combustion chamber after the P_{100} test

Table 2. Combustion tests results

Parameter	P_{wood}	$P_{50\text{-}50}$	$P_{70\text{-}30}$	P_{100}
Average HHV_{dry} of the fuel [kWh/kg]	4.83	5.26	5.43	5.69
Average hot air flow [Nm^3/h]	907	907	907	907
Average hot air temperature [°C]	59.4	62.6	49.8	43.5
Average ambient air temperature [°C]	34.9	35.5	33.4	32.5
Average $\Delta T_{hot\ air\text{-}\ ambient}$ [°C]	24.4	27	16.4	11
Average thermal power [kW]	8.02	8.86	5.39	3.61
Dry pellets consumption [kg/h]	4.41	4.09	3.35	3.31
Average overall efficiency [%]	37.7	41.2	29.7	19.2

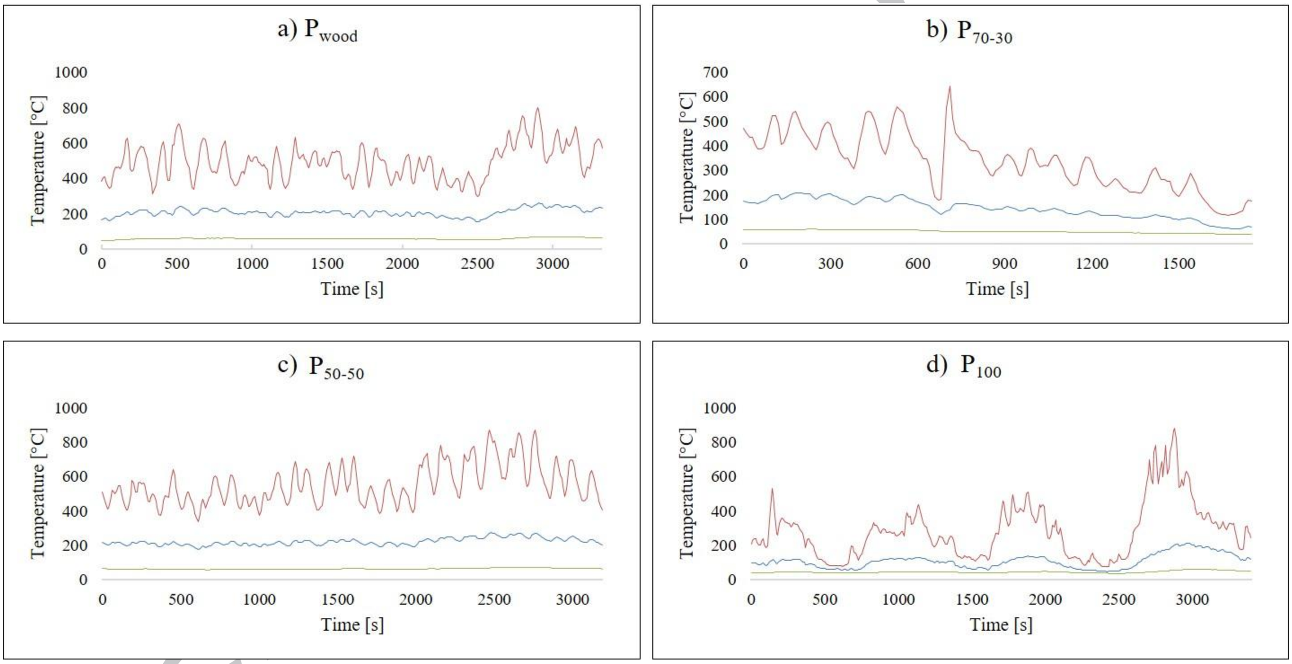

Figure 5. Temperature trends with wood pellet (a), 50%-50% pellet (b), 70%-30% pellet (c), 100% coffee pellet (d).

3.2 The case study

The tests results are applied to the *Caffè Cagliari* roasting coffee company, founded in Modena in 1909. Four tests are performed: pure conifer wood pellet (P_{wood}), $P_{50\text{-}50}$, $P_{70\text{-}30}$ and P_{100}. Today *Caffè Cagliari* produces more than 5 tons of roasted coffee beans per day, through 25 roasting cycles per day. During this process, the roasting machine leads to the torrefaction of coffee beans and the temperature in the roasting chamber passes from 95°C to 220°C. In every cycle the mass of coffee beans decrease from 280 kg to 220 kg: about 22% in weight of water is lost. Considering the roasting machine technical data and the cost of the natural gas, *Caffè Cagliari* spends more than 63000 €/year for the gas supply as reported in Table 3. This article introduces a new concept to a coffee roasting company: by collecting and transforming SCG into pellets, the company can in totality satisfy its heat demand. This causes major savings, the possibility to obtain environmental certifications ("*Certificati Bianchi*") that provide a financial benefit and social and environmental improvements [37].

Table 3. *Caffè Cagliari* natural gas consumption and costs

Parameter	Value
HHV natural gas [36]	47.70 MJ/kg
Natural gas density [37]	0.72 kg/m^3
Natural gas cost [37]	0.62 €/m^3
Gas consumption per day	400 m^3/day
Gas consumption per year	101600 m^3/year
Gas cost per day	248 €/day
Gas cost per year	63185 €/year
Thermal power	159 kW

Literature review also suggests the possibility to extract oil (up to 15% in weight) from SCG [18]. This oil can be converted into bio-diesel and used by the company vans: it could bring to more than 26100 kg of fuel oil from only the quantity of coffee sold in the province of Modena.

3.2.1 The coffee roasting company 2.0

Combustion tests reveal that the best bio-fuel is $P_{50\text{-}50}$. Through the introduction of four new phases, it is possible to pass from a linear economy where the SCG are treated as waste (Figure 6, a), to a circular economy where SCG are collected and used as fuel to generate the heat required for the roasting process. The new phases illustrated in Figure 6 (b) are: collection of SCG, drying of SCG, pellet-making and pellet combustion. The collection is easily feasible, because *Caffè Cagliari* weekly delivers the roasted coffee directly to the clients: the vans used for the delivering can return to the headquarter full of SCG that the clients have stored. For the drying process, it is necessary to purchase an industrial dryer; in this case, the recommended dryer is a Allwood rotative dryer [40]. The recommended dryer works with heat from wood-coffee pellets combustion and it can dry 150 kg/h of wet biomass (SCG). For the pellets realisation, a 7.5 kW_{el} Allwood pellet mill is suggested. The machine can produce 120-200 kg/h of pellet. For the combustion phase a Arca caldaie model Granola 250 is recommended [41]. Its thermal power is 250 kW. All the machines technical data are shown in Table 4.

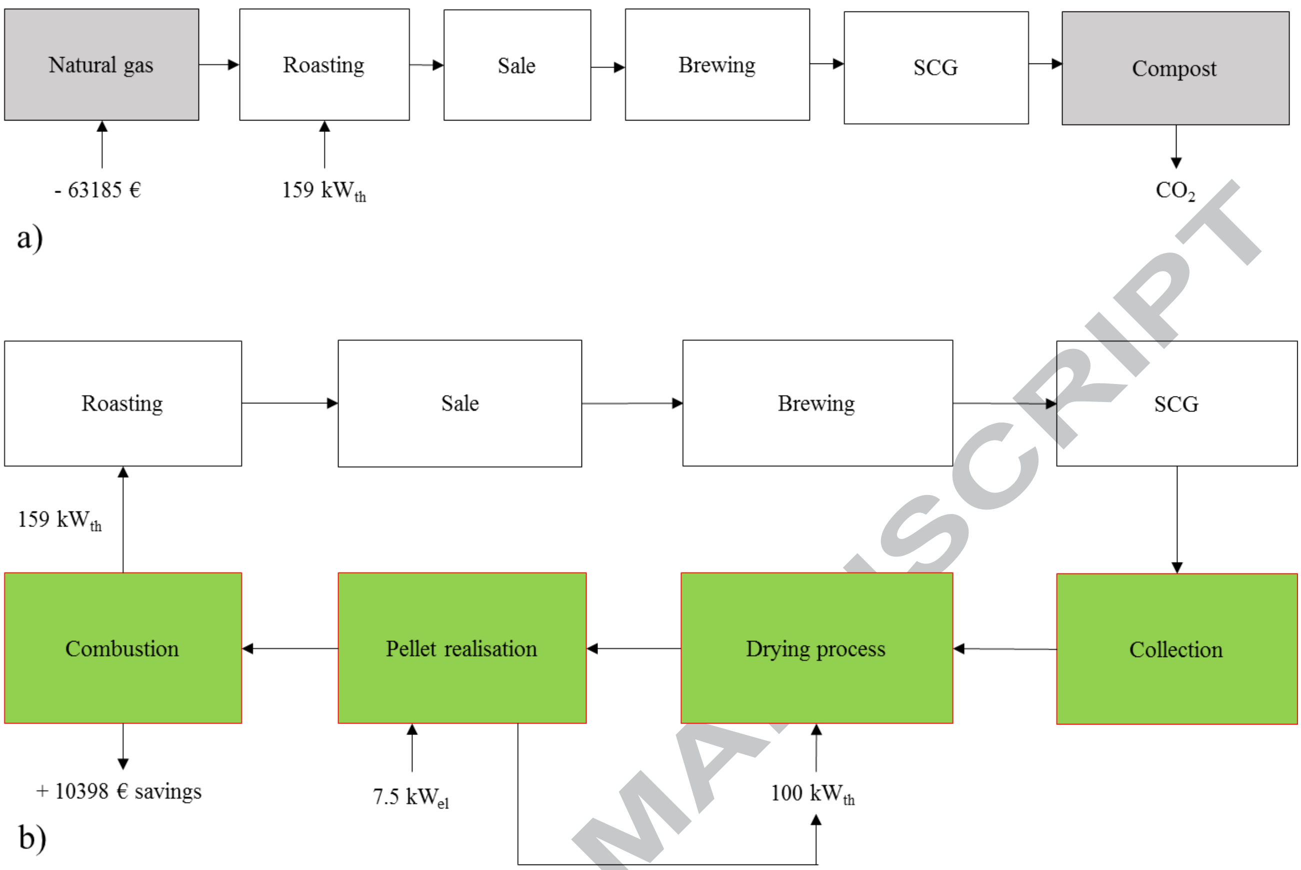

Figure 6. Linear economy of a roasting coffee company (a), circular economy of a roasting coffee company (b)

Table 4. Machines technical data

Parameter	Dryer	Pellet mill	Hot air generator
Cost [€]	10000	3120	19226
Power consumption	100 kW$_{th}$	7.5 kW$_{el}$	/
Power generation [kW$_{th}$]	/	/	159
Treated material [kg/h]	150	120-200	/
Dimensions [mm]	915x6120x2180	/	750x2285x1575
Weight [kg]	2100	225	790

3.2.2 The Scenarios

To reach the environmental and the economic sustainability, three different scenarios are examined (Table 5). Starting from the *Scenario 0*, which represents the actual situation of *Caffè Cagliari*, *Scenario 1*, *Scenario 2* and *Scenario 3* are analysed. All the scenarios consider the SCG collection from only the province of Modena: considering 13 g of SCG produced from every espresso made with 7 g of fresh coffee, about 1300 kg/day can be collected. *Scenario 1* involves the use of P_{50-50}, *Scenario 2* the use of P_{70-30} and *Scenario 3* the use of P_{100}. As shown in Table 5, with *Scenario 1*, *Caffè Cagliari* can satisfy its heat demand for the roasting process simply by using SCG and sawdust pellets.

Table 5. Scenarios results (daily based)

Parameters	Scenario 0 (*status quo*)	Scenario 1 (P_{50-50})	Scenario 2 (P_{70-30})	Scenario 3 (P_{100})
Roasted coffee sold in province of Modena	700 kg	700 kg	700 kg	700 kg
SCG	1300 kg	1300 kg	1300 kg	1300 kg
SCG collected (considering a collection efficiency of 90%)	/	1170 kg	1170 kg	1170 kg
HHV_{dry}	/	5.07 kW/kg	4.83 kW/kg	4.89 kW/kg
SDCG	/	702 kg	702 kg	702 kg
Power generated in the hot air generator	/	198.75 kW_{th}	198.75 kW_{th}	198.75 kW_{th}
Biomass used for the hot air generator	/	869.92 kg	857.06 kg	838.48 kg
Power necessary for the dryer	/	100 kW	100 kW	100 kW
Biomass used for the dryer	/	439.35 kg	432.86 kg	423.47 kg
Difference between collected and used SCG	/	47.37 kg	- 200.94 kg*	- 559.95 kg*
Electrical pellet mill consumption	/	7.5 kW_{el}	7.5 kW_{el}	7.5 kW_{el}
Savings	---	+	++	+++
Combustion quality	+++	++	-	--
SCG self-sustainability	/	++	+	-

* The SCG collection needs to be extended to other provinces.

Considering the SCG collection in the province of Modena only, *Scenario 2* and *Scenario 3*, are impossible to carry out due to the high amount of SCG required for producing enough $P_{70\text{-}30}$ and P_{100} pellets. While this work wants to promote local actions with simple logistics, an extension beyond the Modena province should be possible and needs to be further investigated. In Table 5, three parameters are considered: savings, combustion quality and SCG self-sustainability. The use of natural gas (*Scenario 0*) guarantees the highest combustion quality, but the fuel needs to be purchased from the natural gas grid. Therefore, switching the fuel from natural gas to pellets, produces significant savings proportional to the SCG/wood sawdust ratio. On the other hand, the SCG self-sustainability is inversely proportional to this ratio. In conclusion, *Scenario 1* is the best in terms of savings, combustion quality and SGC self-sustainability.

3.2.3 The CO_2 emissions

In the *Scenario 1* the CO_2 emissions are only due to the electrical consumption of the pellet mill due to carbon neutrality of biomass combustion [42]. Considering an emission factor of 0.337 [$kgCO_2$/kWh] [38] and a natural gas consumption of 400 Nm^3 per day in the company today, the CO_2 emitted in the *Scenario 0* is more than 71690 kg/year while in the *Scenario 1,* is 5135 kg/year. In addition, the unique framework where this research grew, is the one of the small and medium coffee roasting enterprises in Italy where the coffee delivery to the espresso bars is made by small trucks owned by the roasting companies. Is then possible to understand how the SCG collection and transportation to the roasting factory do not further affect the CO_2 emission balance. SCG can be easily picked up from the bars simultaneously during the coffee delivery process.

3.3 The business plan

The business plan for the *Scenario 1* shows a financial feasibility and sustainability. The initial investment includes the initial 38846 € purchase of the new machines (dryer, pellet mill, hot air generator, automatic system for the biomass loading and silos for SCG storage) and 52787 € for the installation, the ordinary maintenance, the electrical consumption, the purchase of the sawdust, and the hiring of a new labourer entirely dedicated to pellets transformation and combustion.

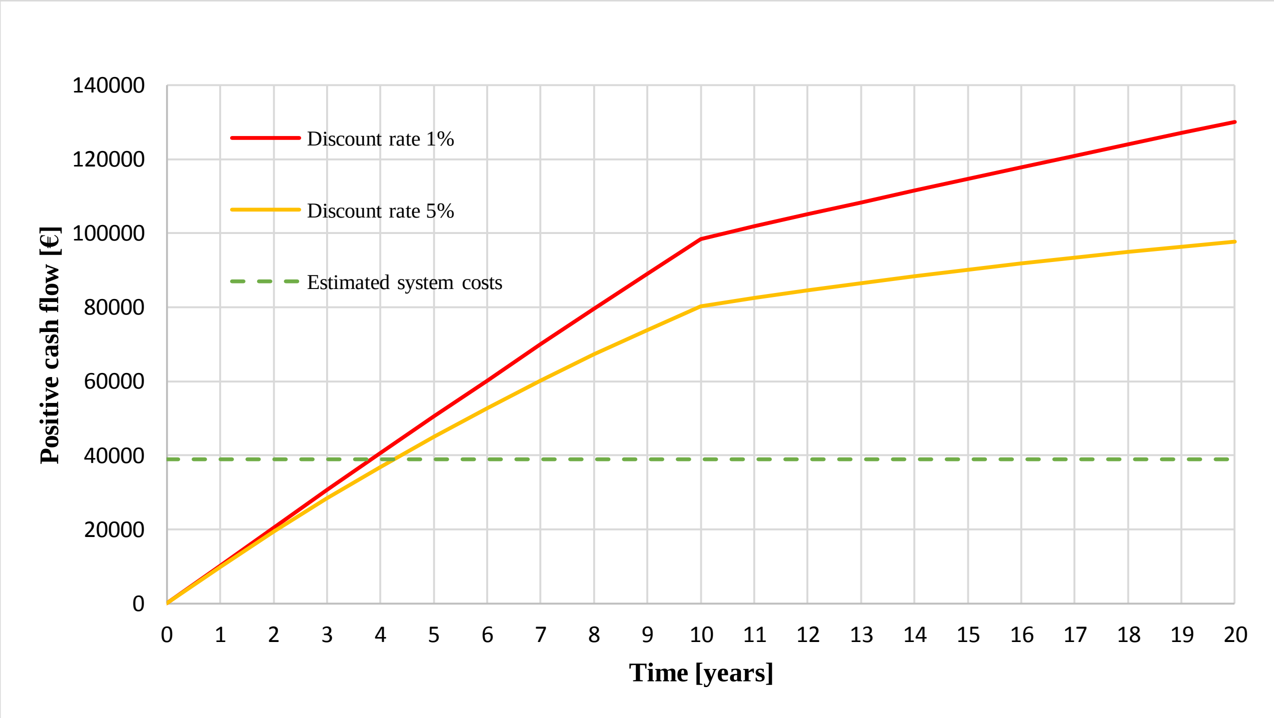

Figure 7. *Scenario 1* present value

Savings of 10398 € per year result from of the environmental certificates and the saving of cost of the gas, with expenditures deducted. Considering discount rates of 1% and 5%, the payback time of the investments is about 4 years as shown in Figure 7 where the dashed green line represents the initial investment. Afterwards 10 years, the Net Present Value will be about 60000 € considering a discount rate of 1% and 40000 € considering a discount rate of 5%. After the 10^{th} year, the environmental certificates will be not available anymore [37] and a gas cost saving of 3685 € can be achieved. Afterwards 20 years, the Net Present Value will be about 90000 € considering a discount rate of 1% and 60000 € considering a discount rate of 5%.

4. CONCLUSIONS

This work introduces a new circular economy model, potentially applicable for every coffee roasting company: by a thermal valorisation of coffee waste, the company can drastically reduce its CO_2 emissions (up to 90%) and at the same time it can generate profit. The model considers a circular economy chain: spent coffee grounds (SCG) collection from bars, drying process to reduce the significant amount of water and realization of pellet, made with a different amount of spruce pine sawdust and coffee. Combustion tests in a 29 kW_{th} air furnace and different scenarios applied to a small coffee roasting company are analysed and the best one suggests the use of pellet 50% coffee – 50% sawdust with a 5.26 kWh/kg HHV_{dry}. An analytical model and a business plan applied to the case study of *Caffè Cagliari*, reveal the short return time of a hypothetic investment: only four years.

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Highlights

- Spent coffee grounds was used as fuel in the coffee roasting process.
- Combustions tests of wood-coffee pellets was done.
- A circular economy model was presented.
- The case study of a small Italian roasting company was discussed.
- Results show that the company satisfy its energy demand with wood-coffee pellets.