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Sustainable solar roasting of coffee beans

TESI DI LAUREA MAGISTRALE IN
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Abstract

With an annual income of $200 billion USD and an expected growth, the coffee industry has a significant economic impact in the food sector.
Sold as whole-bean, instant coffee, coffee pods or capsules, coffee is one of the most marketed food products in the world with an extremely complex supply chain.
Since sustainability is becoming an essential target for the process industry actions to improve the coffee production process need to be investigated.
Specifically, this work is focused on the roasting process, being the most critical operation in terms of environmental impact and final quality of the product.
To make this process more sustainable the fossil fuels, used today to heat up the roasting air, need to be replaced with alternative renewable energy.
The study focused on the research of theoretical models able to predict and describe the coffee beans behavior during traditional and solar roasting. The models were evaluated through the use of data collected from bibliographic sources.
The temperature and moisture profile of coffee beans during traditional roasting were firstly developed under the main assumptions of the process.
Then three alternatives solutions were analyzed. The first faithfully simulate the traditional process with an hot air flow that pass through the beans and a system of parabolic trough to heat up the air was dimensioned.
Then, beans were put in direct contact with concentrated solar energy in two different roasting configuration and with a temperature and moisture profile models the feasibility of the processes were evaluated.
The main parameters considered are the roasting time, the final beans temperature and the flavour and taste of final product. The first two can be deduced from the formulation adopted for the various cases, while the third requires a specific laboratory analysis to effectively determine if the roasting with direct contact leads to the same quality of the traditional process.

Key-words: sustainability, roasting process, coffee beans, temperature, mathematical model

Estratto

Con un introito annuo di 200 miliardi di dollari e una crescita continua, l'industria del caffè ha un impatto economico significativo nel settore alimentare.
Venduto in grani interi, caffè istantaneo, cialde o capsule, il caffè è uno dei prodotti alimentari più commercializzati al mondo con una filiera estremamente complessa.
Dal momento che la sostenibilità sta diventando un obiettivo essenziale per le azioni del settore, è necessario investigare su quali possano migliorare il processo di produzione del caffè.
Nello specifico, questo lavoro è focalizzato sul processo di tostatura, essendo l'operazione più critica in termini di impatto ambientale e qualità finale del prodotto.
Per rendere questo processo più sostenibile i combustibili fossili, oggi utilizzati per riscaldare l'aria di torrefazione, devono essere sostituiti con energie rinnovabili alternative.
Lo studio si è concentrato sulla ricerca di modelli teorici in grado di prevedere e descrivere il comportamento dei chicchi di caffè durante la tostatura tradizionale e solare. I modelli sono stati valutati attraverso l'utilizzo di dati raccolti da fonti bibliografiche.
La temperatura e il profilo di umidità dei chicchi di caffè durante la tostatura tradizionale sono stati sviluppati in primo luogo sotto le principali ipotesi del processo.
Poi sono state analizzate tre soluzioni alternative. Il primo simula fedelmente il processo tradizionale con un flusso di aria calda che passa attraverso i fagioli e un sistema di trogolo parabolico per riscaldare l'aria è stato dimensionato.
Successivamente, i chicchi sono stati messi a contatto diretto con l'energia solare concentrata in due diverse configurazioni di tostatura e con modelli di temperatura e profilo di umidità è stata valutata la fattibilità dei processi.
I principali parametri considerati sono il tempo di tostatura, la temperatura finale dei chicchi e il sapore e il gusto del prodotto finale. I primi due possono essere dedotti dalla formulazione adottata per i vari casi, mentre il terzo richiede una

specifica analisi di laboratorio per determinare efficacemente se la torrefazione a contatto diretto porta alla stessa qualità del processo tradizionale.

Parole chiave: sostenibilità, processo di tostatura, chicchi di caffè, temperatura, modelli matematici.

Contents

1 Introduction

The objective of the carried-out research was to evaluate alternative and more sustainable techniques to perform coffee roasting, able to reduce the environmental impact of that process and, at the same time, maintain the high quality of the final product.
With 3 billion cups consumed each day an expected growing demand coffee represent one of the most important internationally traded food commodities.
The coffee industry has a huge impact both in terms of economic value and carbon footprint.
In recent years, the increasing awareness in sustainability related aspects such as greenhouse gas emissions has result in the need, for large scale producers, to rethink traditional production process in a less impactful way.
The goal is therefore to develop production process as green as possible, able to provide the consumer with a finished product of high quality.
By analysing the coffee supply chain, it has emerged that the critical phase, characterized by the highest carbon footprint, is the roasting one.
Roasting is a very complex process due to the simultaneous heat and mass transfer that take places which greatly influence the colour, aroma and flavour of the final produced product.
Hence, the need to firstly analyse the roasting phenomenon through the development of a mathematical model and then evaluate possible alternative methods.

The considered process has been simplified by assuming that the mechanism of greatest importance is the convective heat transfer between hot air and coffee beans, thus neglecting the heat transfer with the roaster and the heat generated by exothermic reactions. However, the water evaporation phenomena is considered and regulated by internal diffusion.

Once the traditional model developed has been validated, two different alternatives have been proposed:

a. Traditional roasting with a solar energy based air heating,

b. Total solar energy based roasting.

With the first one roasting is performed exactly as in the traditional way: coffee beans are exposed to hot roasting gases which allow to roasting reactions to take place.

In the second model, on the other hand, beans are heated up by concentrated solar radiation and the hot air flow is not required anymore. This situation happens both in the open drum and closed drum analyzed.

Since no set rules exist to produce a specific roast of coffee the artisan roaster needs to continuously analyse the beans during the roasting process, and accordingly adjust the roasting conditions to attain the preferred roast degree. Thus, the bean's temperature and moisture profile, that allow to control the process have been investigated for each alternative.

Later, the system configurations proposed have been dimensioned verifying the feasibility of the process in terms of space required and roasting time per mass of coffee loaded.

Finally, accordingly to the purpose of the model developed to reduce the environmental impact of roasting process, the fuel saved and consequently the CO_2 emissions avoided have been estimated.

2 Coffee overview

2.1. Coffee market

Coffee is the second best-selling product in the world after petroleum and its by-products. With over 3 billion cups of coffee being consumed on average each day, the coffee industry has significant global economic impact.

The great consumption is not only due to its unmistakable taste, but above all to the irreplaceable role it has taken on in the daily lives of millions of people. Drinking coffee has become an habit and a convivial way of socializing and sharing time with others.

The majority of the world's coffee beans are grown in America, Central Africa and South Asia but can also be cultivated in other favourable, humid climates.

According to data from the International Coffee Organization (ICO) [43], global production in 2020 was 165.053 thousand 60 kg bags, 4.48% lower than the previous year. On the other hand, 169.634 thousand 60 kg bags were marketed in the same year, down 2.2% from 2019 due to Covid-19 emergency. These data show a demand for coffee that for years has been greater than production capacity.

Table 2.1: World coffee consumption. (Adapted from International Coffee Organization (ICO))

World coffee consumption In thousand 60kg bags				
	2017/18	**2018/19**	**2019/20**	**2020/21**
World	161 377	168 492	164 346	166 346
Africa	11 087	12 017	12 024	12 242
Asia & Oceania	34 093	36 472	36 002	36 503
Central America & Mexico	5 273	5 431	5 327	5 364
Europe	53 251	55 637	53 372	54 065
North America	29 941	31 779	30 580	30 993
South America	26 922	27 156	26 898	27 180

Table 2.1 shows the growing trend in coffee consumption and also that Europe is the main consumer of coffee, thanks to a thousand-year history of coffee drink in this continent. Finland is the country with the world's highest per capita coffee consumption of 12 kg/year, followed by Norway with 9.9 kg/year. In Italy, consumption is 5.8 kg/year [43]. Although coffee culture is more deeply rooted in our country, the difference in consumption lies in people's preferences. Northern European countries prefer long coffee to the espresso coffee commonly drunk in Italy.

The fact that Europe is the largest consumer also makes it the largest importer of green coffee as it does not have the environmental capacity to grow large quantities. In 2019, Europe imported 80.057 thousand 60 kg bags of coffee of which 13.6% was imported to Italy (equal to 10.914 thousands of 60 kg bags). The second largest importer is the United States of America with 30.854 thousands of 60kg bags.

The big exporters and producers of green coffee beans are Brazil, Vietnam, Colombia, and Indonesia again according to International Coffee Organization [41] data. In the year 2019/20 they produced 58.211, 30.487, 14.100 and 11.433 thousand 60kg bags of coffee respectively accounting for 69,2% of the global production.

Brazil alone produces 1/3 of the total marketed coffee and in the same year it exported 69.9% of its crop as green coffee, while Vietnam Colombia and Indonesia exported respectively 89.8%, 96.9% and 55,4% of its crop.

2.1.1. Price and demand variation

Although production is almost constant over the years, the price of coffee is subject to various fluctuations and market variations. It is influenced by the mismatch between supply and demand. In the last five years production has always been between 160.000-170.000 thousand bags while demand has grown continuously. This trend does not seem to want to stop according to Research and Market magazine, the growth of the global coffee market will be at a CAGR of 7.6% in 2025, which corresponds to a gain of 144.68 billion USD (compared to 107.93 billion USD in 2021) equal to a demand for raw material in excess of >175.000 thousand bags.

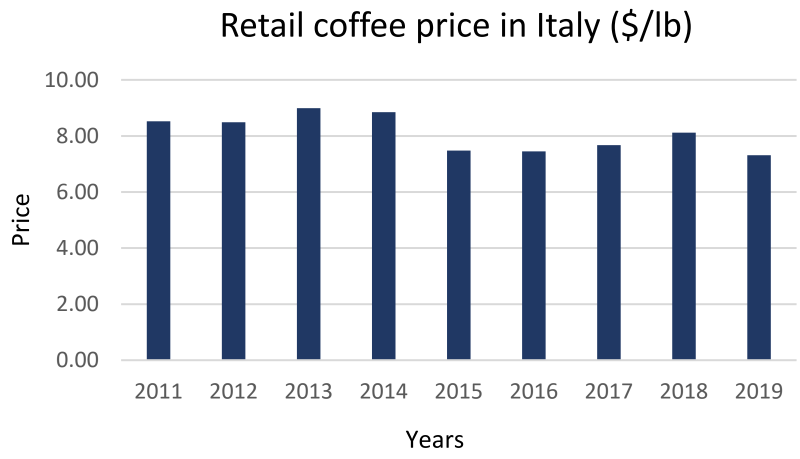


Figure 2.1: Retail coffee price in Italy. Adapted from ICO

Changes of coffee price between 2012 and 2019 are shown in Figure 1.1. In 2013 it reached its peak of 8.99 $/lb, and then decreased by 1.5 $/lb in the following two years. According to [42] estimates, due to Covid-19, worsening weather conditions and increasing gap between demand and supply, it will reach a new high in 2023. The increase in coffee demand is due to many reasons: the increased sales in Asia (China) is one of the most important. According to the data from the China Coffee Association Beijing (CCAB), coffee consumption is increasing at an annual rate of 15%. This market is dominated by foreign brands like Starbucks, Nestlè, Blenz that attract new generations of Chinese looking for new experiences and a more western lifestyle.

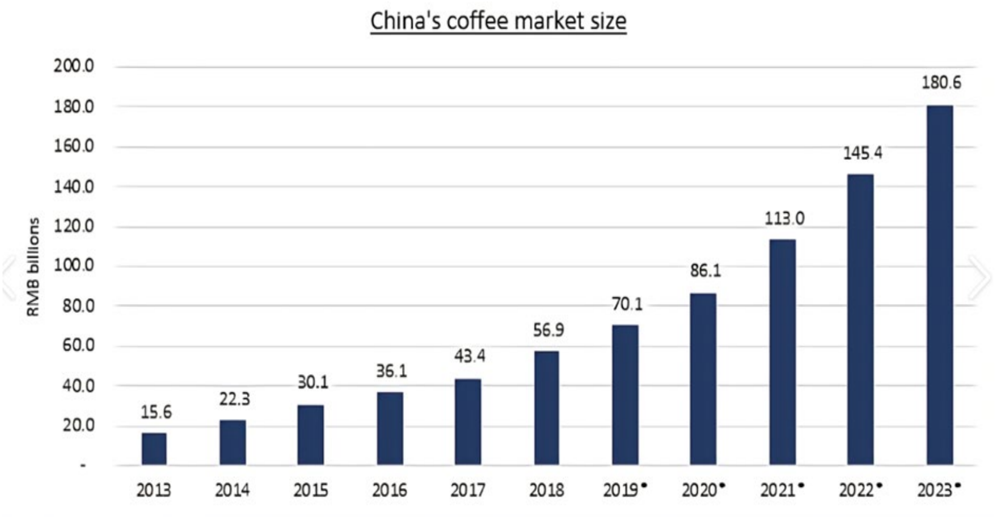


Figure 2.2: China's coffee market size. Adapted from ICO.

2.2. Product classification

The worldwide diffusion of coffee in recent decades has meant that companies have moved in a way to provide a product suitable for every consumer. For example, in Italy the culture of espresso coffee in a moka pot is still predominant as a break from work or as a pleasure. In northern Europe, North America and Asia, on the other hand, consumers prefer a long coffee to be drunk quickly while working.
Many people are looking for a wider coffee experience and choice for a different taste within every cup. Other people cannot take caffeine but do not want to give up their coffee.
These different demands have led manufacturers to market coffee in various forms such as instant, single-serving pods, decaffeinated as well as the common coffee beans and ground coffee.
Nowadays, coffee is sold in 4 main forms: instant, capsules, ground and beans, each one is also present in a decaffeinated version.

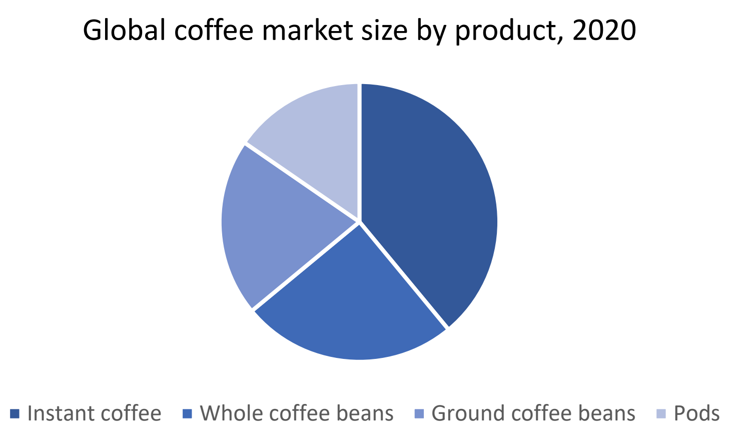


Figure 2.3: Global coffee market size by product. (Maximized market research).

The pie chart shows how the market is divided by retailers' coffee sales accordingly to Maximize Market research, [53].
Instant coffee was the best-selling coffee in 2020, with a market share of 39%. It has reached huge demand in currently years keeping pace with an increasingly fast and smart world. The taste of instant coffee is milder than the classic coffee, but it is quicker to prepare. Coffee beans after roasting are brewed and freeze-dried, requiring ad hoc machineries.

Roasted whole coffee accounted for 25% of sales in the same year. It needs to be ground before use therefore it is mainly sold to private individuals such as bars and restaurants as it is synonymous with freshness. The third best-selling type is ground coffee with a market share of 20,6%. It is very popular and widespread in Italy because it can be consumed at home, using a traditional moka. Bars and restaurants are also buying this type of coffee for use in coffee machines.

The last product with 15,4% sales is capsules and pods. Unlike the previous ones, the customers must own a specific coffee machine. Each pod or capsule correspond to one coffee cup. There are a wide variety of flavors on the market, making it easier to enjoy different coffee, within the same day, satisfying those who look for coffee not only as a break but also as a pleasure and an experience.

Although the wide variety of coffee on the market, in different forms and qualities, meeting the needs of all consumers and the social, economic and environmental impact of a new product should be considered. Costs, waste production, packaging are some of important aspects that a company needs to assess before marketing a product.

Table 2.2: Differences between coffee products.

	Instant coffee	**Whole coffee**	**Ground coffee**	**Coffee pods**
BEAN PROCESS	Freeze-drying	Traditional method	Traditional method	Traditional method
TIME	Very fast	Very slow	Slow	Fast
TASTE	Little intense	Intense/strong	Intense/strong	Many flavors
PACKAGING	Stickpack packs	Paper bag	Vacuum multi-layers bag	Aluminium or plastic pods
COST	Low	Medium	Medium	High
WASTE	Packaging wet spent coffee	Packaging spent coffee	Packaging spent coffee	Packaging Aluminium pods spent coffee

2.3. Coffee supply chain

The typical coffee supply chain is a lengthy process that involves beans' growth, harvesting, drying, packing, bulking, blending and finally roasting. In between this process, the beans go through international transporters, export sellers and retailers like grocery stores, cafes, and specialty shops. The aim must be to develop a lean and responsive SC capable of dealing with the seasonality of the product and unforeseen climatic events, difficulties in coordinating and sharing information along all the chain, quickly meeting the customer needs and being sustainable. In this direction the right management of the supply chain configuration is essential for the system performance and profitability.
Being an agricultural product, coffee grows in certain area, but it's produced in specialized plants able to serve regional market, thus, the global configuration of the SC is a "shopper" one: international import, local manufacturing and deliver to regional market.

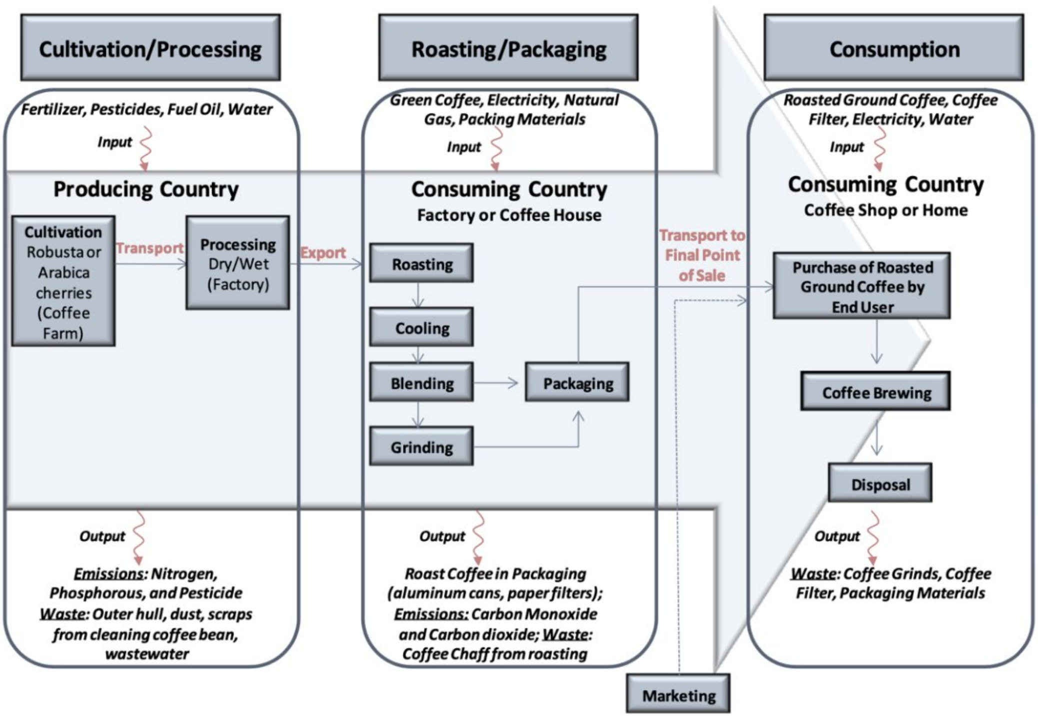


Figure 2.4: The coffee value chain.

The actors and intermediaries are farmers and cooperative (around the world), exporter-importer, processing company and retailers (local country). Each player corresponds to a step in the supply chain.
At the beginning of the value chain farmers are responsible to control coffee plants growth, cherries ripening and they're consequently harvesting.
After harvesting, fruit’s pulp and seed must be removed by farmers directly or cooperative. This process can be done with three different methods: wet, dry, and semi-dry processing that will be explained in the following chapter.
The dried beans are hulled, sorted, grated then thy are packed in standard 60 kg bags and made ready for shipping.
The raw material is transported from exporting country by a variety of means like trucks, trains, and cargo ships to the consuming country where roasting and blending take place. Beans, during transport, are sensitive to moisture and spoilage, so they should be shipped as quickly as possible in well-sealed bags.
The buyer decides to purchase the product only after accepting its quality.
The quality analysis of the sample can be made on a representative sample taken from different bags from the same batch, by a generic sample, taken from different bags from different batch, or by an offer sample provided by the seller to attract new customers.
The raw material quality analysis determines not only the final product but also the purchase contract and the type of relationship between companies and suppliers.
In the purchase contract the two players must agree on the terms of costs and responsibility transfer for good in accordance with Incoterms.
The most common Incoterms in coffee beans trades are FOB, CIF and FCA (European Standard Contract for Coffee, [28]).
FOB is “Free on Board”: the seller must deliver the coffee onto the ship at the port in the country of embarkation. Any overland transportation costs from mills or warehouses to the port of origin must be paid for by the seller. The buyer agrees to book and pay for oversea shipping, insurance, and any drayage/transportation, customs, and overland freight costs incurred on arrival to the port of destination.
Cost, insurance, and freight (CIF) is an international shipping agreement, which represents the charges paid by a seller to cover the costs, insurance, and freight of a buyer's order while the cargo is in transit. CIF only applies to goods transported via a waterway, sea, or ocean.

The FCA "Free Carrier" rule requires the seller to deliver the goods to the buyer or its carrier either at the seller's premises loaded onto the collecting vehicle or delivered to another premises (typically a forwarder's warehouse, airport or container terminal) not unloaded from the seller's vehicle.
Generally, importers are large coffee companies. Within these firms the dried coffee beans are roasted and transformed into the final product. A difference in SC between the largest roasters as Nestlè, Starbucks, Kraft, Lavazza and smaller roasters like Illy [40], is that the largest generally rely upon traders to generate their supply of coffee rather than dealing directly with producers whereas smaller, especially specialty roasters tend to secure their supplies directly from producers and their organizations (Byrnes et al., [13])
The roasting process is the key operation of the supply chain in economic and sustainable terms.
The final quality of the product depends on the roasting: higher quality means higher sell price. Different roasting method add value to the final product. Similarly, roasting has a major impact on the environment: to obtain roasted coffee, air must be heated above 250 degrees by burning natural gas. Exhaust process gases are rich in CO2 and VOC2 which are the responsible of environmental pollution.
After cooling and packaging, final goods are distributed to retailers.
The main retailers are large supermarkets and discount stores or private businesses such as bars and restaurants. In some cases, such as Starbucks, the roasters are also direct retailers.
As already mentioned, coffee is sold in beans, ground, pods or instant.

2.3.1. Supply chain management

Nowadays efficient supply chain management is what enables a company to have a competitive position in its industry, differentiating it from others. SCM can be defined as "the management of all activities, information, knowledge and financial resources associated with the flow and transformation of goods and services from the raw materials suppliers, component suppliers and other suppliers, in such a way the expectations of the end-users of the company are being met or surpassed" (Van Weele et al., 2005) or "management of relationships upstream and downstream with suppliers and customers to deliver a higher value to the customers at a lower cost to all supply chain" (Christopher et al., [16]).

In the case of coffee, the optimization of the SC by improving the management of each step is mainly linked to 3 critical points: purchasing policies, coordination between parties, inventory handling.

Purchasing policies regards raw materials, subsidiary materials and packaging.

The procurement department, after analysing the various purchasing categories with the Kraljic matrix, must choose and find the right supplier, which can simultaneously achieve quality, quantity, deadline and price, without forgetting the company's culture and values. As with most agricultural products, purchasing strategies are based on a risk management approach. Companies therefore tend to have more than one supplier, opting for multiple or dual sourcing, aimed at creating a close, long-term relationship with the growers themselves.

Purchasing strategies influence the financial aspect of the supply chain but also the sustainable and social aspect. As we will discuss later, the selection and choice of producers is more and more aimed at giving value to those who cultivate using sustainable methods, who respect the environment and who guarantee adequate pay for the workforce.

But choosing the right supplier is not enough to achieve high performance; companies need to be able to manage communication and information throughout the chain. Data sharing is essential to know in real time what the sales demands are and consequently the decisions to be taken in terms of procurement, inventory and production.

Implement a knowledge portal about coffee-based business activities can help. Knowledge portal is the implementation of information technology that contains information relevant to a business process. This system allows you to share feedback quickly and at the same time have a historical archive of activities.

2.3.2. Sustainability

In recent decades, consumer attention has focused on environmental and social aspects in addition to economic ones. The interest in healthier, more sustainable, and planet-friendly products has led companies to review their supply chain management and planning to meet these new requirements.

This led to the need to include sustainability plans as a reference for short, medium, and long-term decisions.
Supply chain initiatives and actions focused on improving environmental impact vary significantly from product to product.

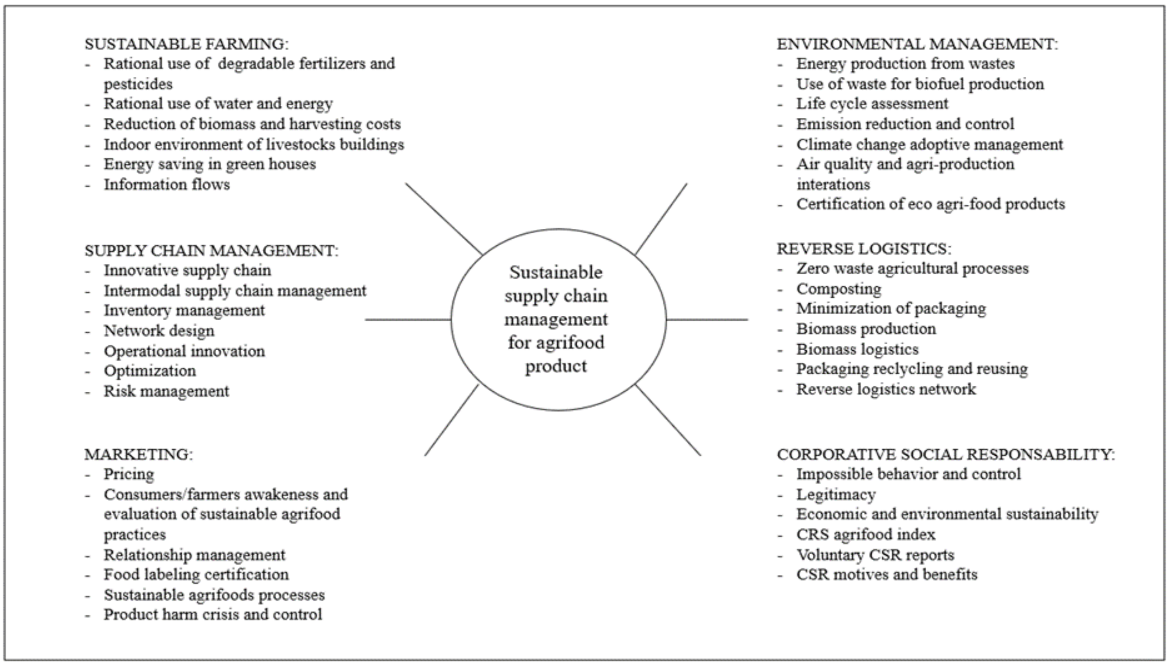


Figure 2.5: Six factors influencing sustainability in agri-food sector (Adapted from Nguyen and Sarker, [60]).

For agri-food products are identified six main factor (Nguyen and Sarker, [60]) influencing sus*ta*inability, reported in Figure 2.5.
As can be seen, the scope for action is diverse and wide, but it should be remembered that only a small part is related to short-term decisions. Integrating a sustainability plan is unlikely to bring immediate tangible results.
Although every step and operation in the supply chain can be made more sustainable, companies face barriers that slow down this process. The first obstacle is the economic one: being sustainable requires large investments without the certainty of a high benefit/cost ratio. Biomass upgrading plants, heat recovery systems, eco-friendly transport are some examples of how making the coffee SC sustainable comes at a significant cost.

The second obstacle is the geographical and social distance between the countries producing the raw material and those producing the final product. Coffee is grown in rural areas of developing countries, according to local culture and tradition. In many cases, farmers are not interested in sustainability aspects or in the development of their activities; this is compounded by language differences and ineffective organization in terms of shared information and values.
In order to encourage companies to follow the path of sustainability along the product supply chain, national and international bodies have moved to promote and recognize sustainability and product quality certifications. The International Standard Organization has defined several relevant certifications that can be achieved by various companies. The ISO 14001 certification covers the management and control of the environmental impacts of an industrial activity. ISO 50001 is based on a systematic approach to energy management, which enables the achievement of continuous improvement in energy performance. This makes it easier to integrate energy management into our overall efforts to improve quality and environmental management, always with a view to sustainability. A relevant standard in the coffee industry is UTZ certification. This label is applicable to all organizations working in the tea, coffee and cocoa supply chain. This certification is awarded to those companies that concretely pursue sustainable agriculture and seek equal rights and conditions for workers throughout the supply chain.

2.3.2.1. End of life: coffee waste reutilization

Coffee production and use generates a significant amount of waste like coffee husks, pulp, silverskin and spent coffee.
Coffee husks are the main by-product of dry process. For 1 ton of fresh coffee cherries, 0.18 ton of husks are released (Blinova et al., 2017) [8]. Coffee husks are composed of 58 – 85% of carbohydrates, 8 – 11% of proteins, 0.5 – 3% of lipids, 3 – 7% of minerals, and minor amounts of bioactive compounds, such as caffeine (~ 1%), chlorogenic acid (~ 2,5%) and tannins (~ 5%) are also present in this residue (Cruz et al., [21]). Many application approaches have been studied for coffee cherry husks re-utilization, as substrate for biogas (Cruz et al., [21]) and alcohol production, bio sorbents for the removal of heavy metals from aqueous solutions bio sorbents for the removal of dyes from aqueous solutions (Cruz et al.,[21]), bio sorbent for defluoridation of water, converted into fuel pellets or extracted for bioactive

substances recovery (Cruz et al., [21]). Besides, coffee husks demonstrated to be suitable candidates for a more direct use as substrate for edible mushrooms production or composting (Nguyen et al., [60]). Coffee husks are also utilized as a potential functional ingredient in food production using the ground coffee husk as a food supplementary for usage in smoothies, granolas and juices. The caffeine and tannins in coffee husks, which are negative in environmental perspective, could be extracted for use in "energy drinks". The high content of dietary fibers in coffee husk constitutes a problem for the development of a beverage, but the fibers can be included in a food product of "energy bars", by grinding the whole coffee husk, and thereby including all antioxidants and fiber into the product. The coffee husk could also be launched as allergic friendly, since it is naturally gluten free. Using the coffee husk for brewed tea is called coffee cherry tea. Coffee husk is a useful substrate for the mold-, yeast- and enzyme production, owing to its high number of fermentable sugars.

Coffee pulp is the first by-product obtained during wet or semi-dry processing and represents 29% dry-weight of the whole cherry. For every 2 tons of commercial green coffee produced, 1 ton of coffee pulp is obtained. Coffee pulp comprises the exocarp (outer skin) as well as the mesocarp (fleshy portion) (2). It is essentially rich in carbohydrates (21 – 32%), proteins (5 – 15%), fats (2 – 7%), and minerals (9%), and contains also considerable amounts of tannins, polyphenols and caffeine (2, 29). The organic components present in coffee pulp (dry weight) include tannins 1.8 – 8.56%, total pectic substances 6.5%, reducing sugars 12.4%, non-reducing sugars 2%, caffeine 1.3%, chlorogenic acid 2.6% and total caffeic acid 1.6% (Cruz et al., [21]).

Similarly to coffee husks, coffee pulp has been studied to be reused for composting, biogas production bioethanol production converted into fuel briquettes or pellets enzymes production such as pectinases or cellulases, and for food production.

Coffee silverskin, frequently known as "chaff", is the first coffee industry residue produced in consuming countries since it is released during roasting if the leaves were not polished before shipping. It consists of the tegument of coffee beans, and thus has a very low mass, comprising 4.2% of the green coffee bean, with reduced environmental impact highly rich in soluble dietary fiber (54% of total dietary fiber) and compounds with antioxidant capacity, particularly phenolic compounds (Cruz et al., [21]). Published data on coffee silverskin reuse are scarce. Aiming at the extraction value-added compounds, some authors have showed that this coffee residue constitutes a fine source of antioxidants and dietary fibers and may be considered as a new potential functional ingredient. Furthermore, coffee silverskin maybe used as support and nutrient source during the fructooligosaccharides and β-furctofuranosidase production by Aspergillus japonicus under solid-state fermentation conditions, used as raw material to produce fuel bioethanol (Cruz et al., [21]).

Spent coffee grounds (SCG) are the waste product from brewing coffee. About 0.91 g of the spent coffee grounds are produced per 1 g of ground coffee, and about two kilograms of wet spent coffee grounds are produced for every kilogram of instant coffee made (Cruz et al., [21]). Chemical composition of coffee brews is dependent on the extractive efficiency, which relies on diverse factors, including the coffee species, roasting degree, grinding grade, coffee/water ratio, water quality, temperature, pressure and percolation time. Generally, SCG are composed of 12.4% cellulose, 39.1% hemicellulose (3.6% arabinose, 19.07% mannose, 16.43% galactose), 23.9% lignin, 2.29% fat, 17.44% protein, and 60.46% of total dietary fibers (Ballesteros et al., 2014). It makes them an interesting source of raw materials for different applications. A potential use of SCG has been as a source for biodiesel production bioethanol production (Mussatto et al., [57]), production of fuel pellets as burning fuel in the industrial soluble industry directly (Cruz et al., [21]), production of reusable cups as source of sugars (Mussatto et al., [57]), as composting material and as a biomaterial in the pharmaceutical industry, in the food industry and in the polymer industry.

2.3.3. Life cycle assessment

Life cycle assessment is an objective tool for assessing and quantifying the energy and environmental loads and potential impacts associated with a product.

The LCA methodology is regulated by the ISO 14040's series of standards according to which a life cycle assessment study involves defining the objective and scope of the analysis (ISO 14041), compiling an inventory of the inputs and outputs of a given system (ISO 14041), assessing the potential environmental impact related to these inputs and outputs (ISO 14042) and finally interpreting the results (ISO 14043).

Given the barriers to be overcome to make the product's supply chain fully sustainable, companies perform an LCA to assess which activity has the greatest impact.

In our case, we have provided an example of LCA for the coffee product. The approach chosen is cradle to gate; the steps of the supply chain considered are cultivation, processing and roasting. We have not included the impact of transport for a logistic free analysis because the contribution of CO_2eq emitted per kg of green coffee is the lowest of the supply chain steps and the reduction of the impact is limited to the choice of the most sustainable means.

To perform LCA it is necessary to start from the life cycle inventory (LCI).

The amount of fertilizer strongly depends on soil characteristics, how the amount of water will vary depending on the seasonal rainfall (Dawid et al, [22]).

Table 2.3: Life Cycle Inventory. (P=process flow, E=elementary flow)

Supply chain step	Flow	Unit of measure	Quantity
Cultivation	Fertilizer (P)	kg/ha/year	Nitrogen (Urea): 87,5 Phosporic acid (P_2O_5): 20 Potassium (K_2O): 90
Processing	Water (E)	m3/1ton green coffee	15
Roasting	Natural gas (P)	MJ	6

The amount of fertilizer reported refers to the amount applied each year. As the first harvest usually takes place 4 years after planting, the values used in the analysis will refer to the total amount.

The flows are taken from Agribalyse database in the OpenLCA programme. To calculate the total impact of each step ILCD 2011 Midpoint+ impact assessment method is used. The reference target amount (or functional unit) is 1 kg of roasted coffee.

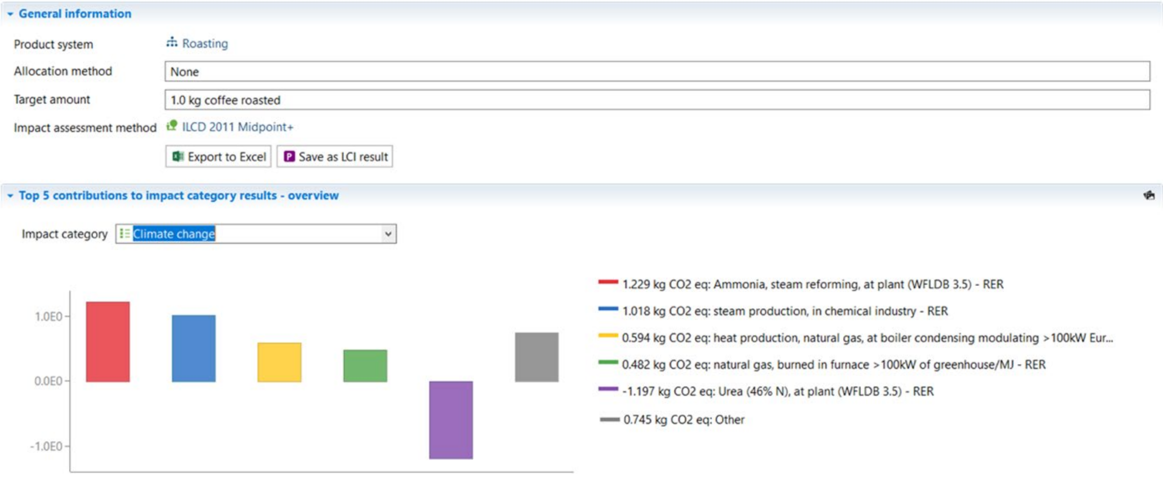


Figure 2.6: General information on coffee LCA. (from Open LCA database).

The Figure 2.6 shows data for climate change category of each elementary or process flow, irrespective of the supply chain step. The impact of each individua flow is significant.

The negative value of CO2 in purple indicates that it is removed from the environment and not emitted. This is due to the use of CO2 as a reagent in the production of urea used as fertilizer.

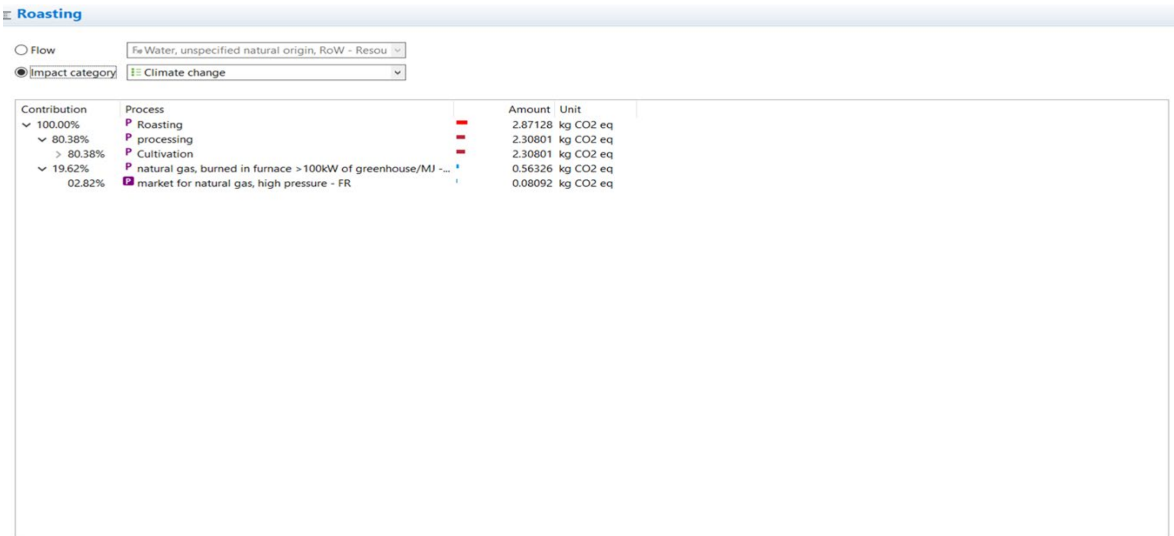


Figure 2.7: Contribution tree of coffee supply chain.

In the contribution tree (Figure 2.7) is reported the assessment of environmental impact for every main step of the coffee production.

As can be seen, the impact of fertilizers results more significant than that of natural gas (80,38% respect to 19,62%). But in order to limit pollution, organic fertilizers can be partially used instead of inorganic ones. Furthermore, the impact analysis of the cultivation step does not consider the CO2 absorbed by the plants for their growth, which significantly reduces the CO_{2eq} value.
The operation that requires more innovation in terms of sustainability is the roasting process, on which we have concentrated our attempt to propose valid solutions to reduce the environmental impact while maintaining the high quality of the product.

3 Coffee production

The process to obtain the final cup of coffee starting from the green coffee beans required many passages discussed in the following chapter. They include cultivation, harvesting, processing, roasting and blending before distribution to the final consumers.

3.1. The coffee bean

The coffee drink is prepared by extracting the aromas from the beans of some tropical plants belonging to Rubiacee family (*genus Coffea*). Coffee plants are grown in tropical and subtropical regions of central and South America, Africa, and South East Asia, mainly in regions with temperate and humid climates (Schenker, 2000). There are more than 100 species of plants, which correspond to as many varieties of coffee. Although a wide choice is available, nowadays the Arabica and Robusta qualities are the most marketed.

Table 3.1: Differences between Arabica and Robusta quality (source: Compoundchem).

	Arabica type	**Robusta type**
Climatic condition	Altitude: 600-2000 mt Temperature: 15° – 24° C	Altitude: 0-800 mt Temperature: 18° - 36° C
Geographical region	Brazil Mexico Perù Colombia Indonesia Honduras	Vietnam Guinea Uganda India
Caffeine content	1.2–1.5 %	2.2–2.7 %

Composition	Chlorogenic acid: 5.5 - 8 % Lipid: 15 –17 % Sugar: 6 – 9 %	Chlorogenic acid: 7 – 10 % Lipid: 10.5 - 11 % Sugar: 3 – 7 %
Key flavours compounds	Dimethylhydroxy furanone 5-ethyl-3-hydroxy-4-methyl-2(5H)-furanone 3-hydroxy-4,5-dimethylfuran- 2(5H) -one	3,5-dimethyl-2-ethylpirazione 2,3-diethyl-5-methylpirazine 4-ethylguaiacol
Taste	Sweet and caramel notes	Spicy and earthy notes
World production	70 %	30%

The main differences between Arabica and Robusta coffee are resumed in Table 3.1. Robusta coffee has a harsher taste, twice the caffeine content, can be grown at sea level, and is more resistant to pests and diseases than Arabica. Arabica coffee is known for its higher quality but can only be produced in warmer temperate zones or in highlands of tropical zones and has a shorter ripening period of about six months.

Coffee cherries are harvested when they become bright-red, glossy, and firm around eight months after the emergence of the flower.

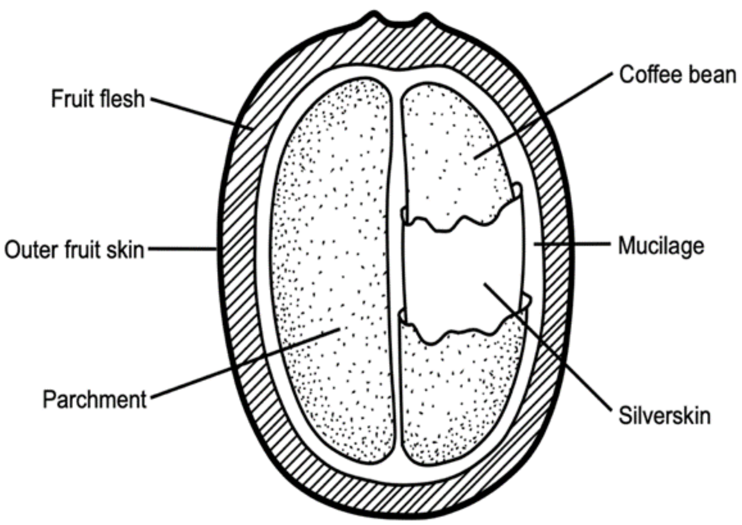


Figure 3.1: Layers of the coffee cherry (adapted from Belitz et al.; [7]).

In each coffee fruit, there are two seeds that grow with their flat sides facing each other, as shown in Figure 3.1. The two seeds are covered with a thin tightly fitted layer called the silverskin, followed by a yellowish looser skin known as the parchment. Both seeds are encased in a viscous and colourless mucilage layer, which is in turn surrounded by the fruit flesh or pulp. The coffee fruit has a tough outer skin that is green in colour, however it turns a deep red when ripe (Esquivel & Jimenez, [27]). Green Coffee beans are the dried-out seeds of the cherry obtained after drying process. Green coffee beans have minimal flavour. However, upon roasting, characteristic coffee aroma is developed due to the complex reactions that take place in the beans. To develop a unique flavour, green coffee beans are roasted according to different time-temperature profiles (Buffo & Cardelli-Freire 2004).

3.1.1. Coffee harvesting

Coffee shrubs need warm and humid weather, typical of equatorial tropical regions. Growing requires stable climatic conditions, pesticides and herbicides, fertilizers and irrigating system. These plants take generally between 4-7 years until they yield its first crop of beans.

The coffee fruit will ripen 12 months after flowering, turning from green to a deep red, and be ready for harvest.

Several methods are utilised to harvest the coffee fruit, with some being more labour intensive than others. In most countries, coffee cherries are picked by hand from the tree, which is a very labor intensive and difficult process, but this ensures that only cherries ready for harvest is collected for processing (Belitz *et al.*, [7]; Moldvaer, [54]). Harvesting can also be done by strip picking, when most of the cherries are ripened the entire branches are stripped. This, however, can cause some immature cherries to be processed, influencing the quality of the final product. Other methods including mechanical harvesting and sweeping beneath the trees to collect the ripe cherries can be used. (Belitz *et al.*, [7]).

3.1.2. Coffee processing

Once coffee berries are collected, they are then transported to processing mills where they are processed, sorted, and graded by size, weight, and form

(Binmahfuth, 2017) [9]. The fruit flesh is separated from the bean that is consequently dryed for the purpose of safe storage. After harvesting, green coffee beans consist of about 60% of moisture and should be dried to 10-14.5% moisture content and stored below 26°C under dry environment (50-75% RH) to maintain the bean quality and to prevent the growth of mould (Rao, 2014). The three primary methods of processing are commonly referred to as the washed process, dry natural process and the pulped natural process (Hoffmann, [38]; Moldvaer,[54]; Rao, 2014).

3.1.2.1. Washed coffee processing

The washed coffee processing method is regarded as the more sophisticated processing method which generally leads to better quality coffee. This is because the fruit flesh is removed from the coffee bean before drying which significantly reduces the chance of something going wrong during the drying stage (Belitz *et al.*, [7]; Hoffmann, [38]).

The freshly harvested coffee cherries are first placed in a flotation tank where the ripe cherries that sink to the bottom are separated from the unripe ones that float. The ripe cherries are then passed through a depulper where its outer skin and fruit flesh are stripped from the beans without damaging it. The pulped beans, which still have the silver skin, parchment and very sticky mucilage layers, are then carried to a water tank where the mucilage layer is removed by means of fermentation. This process takes up to 2 days.

After the removal of the mucilage layer, the coffee beans have a moisture content of about 50 % and is therefore in need of drying, by either mechanical driers or out in the sun. The dried product is stored in this condition until the time of exportation, where it goes through the final stages of processing which consist of cleaning, hulling (removing any remaining layers, including some of the silverskin) and grading (Hoffmann,[38]; Moldvaer,[54]).

3.1.2.2. Dry natural coffee processing

It is the oldest method of processing coffee. The dry natural process is fairly straightforward and the more economical one of the three. Before drying the harvested cherries are sorted to remove any unripe fruit from processing. The ripe cherries are then dried in the sun on tables or in thin layers on patios for several weeks. As the cherries dry, they are raked or turned by hand to ensure even drying and prevent mildew. The drying operation is the most important stage of the process, since it affects the final quality of the green coffee. A coffee that has been over dried will become brittle and produce too many broken beans during hulling, while coffee that has not been dried sufficiently will be too moist and prone to rapid deterioration caused by the attack of fungi and bacteria. After drying coffee is stored awaiting exportation (Hoffmann,[38]). The dry natural process goes through the same final stages of the washed process mentioned above.

3.1.2.3. Pulped natural coffee processing

The pulped natural coffee processing method also called semi-dry processing tends to produce sweeter coffee than the dry natural process. As in the washed process, the cherries are placed in a flotation tank to remove the unripe cherries, after which the ripe cherries are passed through a depulper, removing the fruit flesh (Hoffmann, [38]; Rao, 2014). The coffee beans still encased in the silverskin, parchment and mucilage layer, are now set out to dry. The pulped beans dry quickly, increasing its sweetness and body (this is due to being dried with the sugary mucilage layer). Just like with the above-mentioned processes, the output of the processing phase are green dried coffee beans and solid waste including the outer hull, dust, and scraps from cleaning the cherries which are typically disposed. The green beans are then classified, graded, and exported to the consuming country for roasting and packaging.

Table 3.2: Main characteristics of different processing methods.

	Wet processing	**Dry processing**	**Semi-dry processing**
Coffee quality	Coffee taste is extremely clear and clean with a marked acidity	Coffee taste is strong and full-bodied with a marked bitterness	Honey Coffee, sweetness is the predominant taste
Environmental impact	Critical issue due to the large amount of water required- water depletion	100% sustainable using sunlight but labour-intensive process.	Between the two main methods-drying process must be fast

Cost	High cost due to use of specific equipment	Low cost if natural process. Higher cost in case of hot-air drying machine	Cheaper than the wet method but less than the dry method

The main characteristics of the above-mentioned processing method are reported in Table 3.2. The choice mostly depends on the type of beans to be processed and the final quality desired. Moreover, the economic aspect of the three processing should be taken into account as well as the impact in terms of energy and water consumption.

3.2. Coffee roasting

3.2.1. Roasting Process

The final attractive flavors and aromas that can be found in a cup of coffee is developed during the roasting of green coffee beans that is the most important unit operation to generate a dark color and a brittle texture which make grinding and extraction possible. Roasting is usually done by exposing the green beans to hot gases or surfaces which allows for the roasting reaction to take place, producing the hundreds of chemical compounds to which the aroma of brewed coffee is attributed (Franca *et al.*, [30]). It is very complex due to the hundreds of reactions which includes hydrolysis, polymerization, reduction, oxidation and decarboxylation that takes place during the simultaneous heat and mass transfer within the coffee roaster. How the reactions take place and at what rates, greatly influences the colour, aroma and flavour of the final produced coffee product (Franca *et al.*, [30]; Putranto & Chen, [67]). The entire roasting process can be divided into three steps: drying, roasting and cooling. The slow release of water and other volatile substances takes place during the drying step. This is followed by the roasting reactions. In general, the use of roasting temperature greater than 200°C is required in order to result in desirable chemical, physical and structural changes of the coffee beans which is necessary for the aroma development. (Franca *et al.*, [30]; Rao, 2014; Schenker, 2000). When the desired degree of roast is reached the coffee beans are removed from the roasting chamber and the cooling phase begins. The roasted coffee is quickly cooled to prevent over roasting and to end exothermic reactions that occur within the beans at the later stages of roasting. There are two most common cooling methods used: the beans are either sprayed with water (quenching) before they are removed from the roasting chamber or they are removed from the roaster and cooled with air (Baggenstoss *et al.*, [3]).

3.2.1.1. Bean behaviour during roasting

The complexity of coffee roasting is due to the simultaneously occurring of heat and mass transfer within the bean.

The traditional roasting process consists of heat transfer to the coffee bean by means of hot roasting air. This heat transfer initiates a rise in bean temperature which in return initiates several chemical and physical changes to occur. It is during these changes that the mass transfer takes place by the release of water vapour, CO2, and volatiles, as well as the dry weight mass transfer that occurs. When exothermic reactions occured heat is also released from the bean to the surrounding environment (Schwartzberg, [70]).

At the beginning of roasting, as the coffee bean takes up more heat, a slow release of water and volatile substances occur. The internal temperature of the bean starts to rise and the chlorophyll inside the bean starts to degrade, initiating the colour change from green to yellow (Franca *et al.*, [30]; Rao, 2014).

As roasting progresses, the complexity increase because hundreds of chemical reactions start to occur simultaneously, resulting in significant changes to the bean's chemical and physical properties. Some of the more recognizable reactions include pyrolysis, Maillard reaction, Strecker degradation as well as the degradation of polysaccharides, chlorogenic acids and proteins (Franca *et al.*, [30]; Putranto & Chen, [67]). The nitrogenous heterocycles and brown melanoidins formed during the Maillard reaction initiate the colour changes from yellow to tan to light brown (Rao, [68]).

During this stage, the occurrence of exothermic reactions rapidly increases the beans' temperature and generate CO2. The amount of CO2 generated is greatly dependent on the coffee type and the conditions under which it is roasted. Large amounts of CO2, along with some water and volatile substances, are released with an audible cracking sound. Moreover, the pressure within the bean becomes high and the bean doubles in size while it becomes half as dense, due to the formation of internal pores and pockets as the gases are released (Schwartzberg, [70]).

The structural changes that occur during roasting, which includes the decrease in weight and density, the increase of bean size and the expansion of internal pores, are directly connected to the amount of CO_2 generated and released.

All these reactions that take place inside the coffee bean during roasting, produces large amounts of volatiles and more than 800 different compounds that are considered responsible for the final aroma and flavour of the coffee bean (Franca *et al.*, [30]; Schenker *et al.*, [71]).

During these reactions takes also place the caramelization of the sugar inside the coffee bean that turns the coffee from the light brown to a darker brown (Rao, [68]). As the roasting process continues and the bean temperature increases, most of the compounds within the bean has been degraded and after the initial release of CO_2, the pressure inside the bean begins to increase again due to the still ongoing reaction and formation of gases. A second crack, again characterized by a cracking sound, is reached when the pressure becomes too high and along with the release of gases, internal oils are forced to the surface of the beans. The second crack further weakens the cell structure making the coffee bean brittle and light in weight (Hoffmann, [38]; Moldvaer, [54]). Roasting induced changes in pore structure have major impact on the final product quality, in fact the pore structure control the mass transfer phenomena during storage and may determine gas adsorption and desorption properties of coffee beans. This are strictly connected to oil migration to the surface of the bean that can be regarded to be a sensory risk for the next step of production.

3.2.1.2. Parameters influencing the roasting process

The coffee roasting process is influenced by many different factors, such as the quality of green beans, the roasting conditions, the time since the beans are roasted, and the type of water used for brewing.

The quantity of heat transferred to the beans presents the most important parameters of roasting process and it can be determined from the final bean's temperature and roasting time. If not enough heat is transferred at the beginning of the roasting process (which may be due to the roaster type used or the conditions of the roasting air) the coffee beans will not dry sufficiently allowing for uneven roasting to occur during later stages and the optimal coffee flavour will not be reached (Hoffmann, [38]; Rao, [68]).

Another factor that can influence roasting is the composition of the green coffee bean, which is highly dependent on the climate it is grown in, and which has great influence over the internal structure of the beans, the processing method used as well as the bean's species and origin (Belitz *et al.*, [7]).

3.2.2. Traditional Roasting technology

Modern coffee roasters work based on hot roasting gas passed through constantly mixed beds of coffee beans or through streams of beans cascading or suspended in the roasting air (Clarke et al., [17]). In most roasters, the roasting air is heated by an open flame and the main source of heat transfer is convection from the hot air to the beans (Schwartzberg, [70]). During roasting, the silverskin will flake off the coffee beans and be carried away by the hot air, therefore the hot air leaving the roasting chamber is usually passed through a cyclone where the chaff is separated from the air. After the separation the air is either discharged into the atmosphere, directed back to the open flame for reheating or sent through an afterburner to oxidize any volatile compounds or CO in the roasting air (Schwartzberg, [70]).

The two most frequently used roasting methods include roasting in a rotating drum and roasting in a fluidized bed (Hoffmann, [38]).

The rotating drum roaster is one of the most used roasters today, especially by craft roasters. It consists of a horizontal roasting drum with spiral flights running along the inside of the drum in order to axially mix the beans (Hoffmann, [38]; Schwartzberg, [70]). Inside the roasting chamber (rotating drum) heat is transferred by conduction, as the beans come into direct contact with hot metal surfaces, and convection, as the hot air flows through the drum.

In this configuration high temperatures are needed for long roasting times in fact the process can take up to 18 minutes which can cause some beans to burn and often leaves oil and char deposits on the chamber walls. Due to the nature of the roaster, this is difficult to clean causing later roasts to develop a pungent, smoky taste.

In a fluidized bed roaster, the heat transfer happens almost exclusively by convection. High volumes of air, preheated by an open flame, enters the roasting chamber at the bottom, where the hot air simultaneously circulate and heat the moving beans. The high volumes of air are needed to keep the beans airborne (Rao, [68]). The roasting process is significantly shorter in a fluidized bed roaster than a

drum roaster, due to the higher volume of air that passes through the roasting chamber, making the fluidized bed roaster a high temperature/short time (HTST) roasting process. Fluidized bed roasters have a lower risk of bean-surface burning, due to minimum or no contact with hot metal surfaces inside the roaster, producing a more uniform roasted batch of beans (Hoffmann, [38]; Rao, [68]).
The final quality of roasted coffee is influenced by the design of the roasters and time-temperature profiles used. Although heat transfers during roasting can involve conduction, convection, and radiation, convection by far is the most important mode of heat transfer that determines the rate and uniformity of roasting (Baggenstoss et al. [4]). Coffees roasted in fluidized-bed roaster that is almost exclusive based on convective heating can result in low density and high yield coffee (Eggers & Pietsch [25]). On the other hand, coffees roasted in drum roaster that involves mainly conductive heat transfer have less soluble solids, more degradation of chlorogenic acids, more burnt flavour, and higher loss of volatiles than the fluidized bed roasters.

3.2.3. Stages of the coffee roasting process

Roasting process is made up of five main stages termed the drying, yellowing, first crack, roast development and second crack stages, as discussed in detail below. During the roasting process coffee beans colour change from a light green colour to a dark brown as it is shown in Figure 3.2.

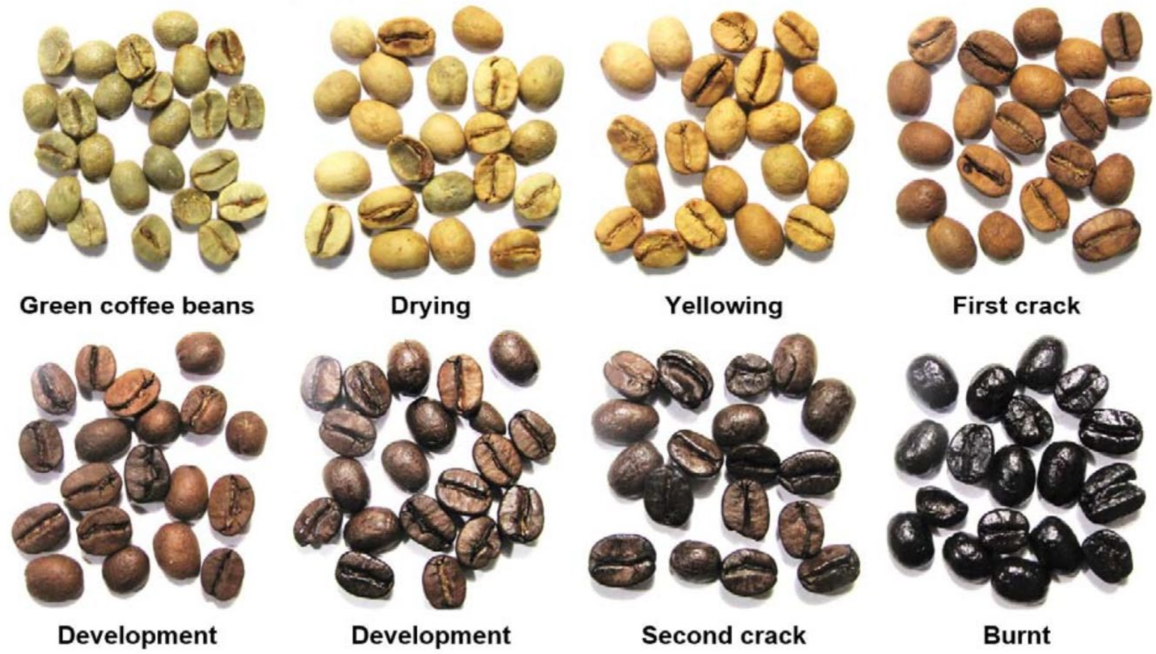


Figure 3.2: Beans colour development during roasting process.

The different roasting stages are an oversimplification of the roasting process for the purpose of making a very complex process more understandable and manageable.

1.Drying

When the roast started a large quantity of energy and heat is required, for it takes a certain amount of time for the coffee beans to absorb enough heat for evaporation to start. Since raw coffee beans generally consist of 9 – 12% moisture evenly spread throughout the beans dense structure, as temperature increases, green beans undergo moisture loss to about 5% in roasted beans. Moisture loss is just the primary change that occurs during drying and occurs continuously throughout the entire roasting process.

2. Yellowing

The coffee beans start to change in colour once enough moisture has evaporated. It is during this stage that sugars are broken down to form acids and the beans give off a bread like aroma. As this stage progresses the coffee beans will start to expand in volume, this leads to the beans' silverskin cracking off and producing chaff (Hoffmann, [38]; Rao, [68]). The chaff needs to be separated from the beans to prevent the risk of fire and this is achieved by the air flowing through the roaster (Hoffmann, [38]).

3. First crack

An accumulation of gases, which consists of mostly carbon dioxide as well as some water vapour, takes place inside the bean once the colour change progresses more rapidly. The accumulation of gases increases the pressure inside the bean until such a point where it becomes too high and the bean breaks open, commonly known as the first crack (Hoffmann, [38]). At this point, a popping sound can be heard, and the bean expands to nearly double its original volume. The first crack usually happens when the roast temperature reaches 165 to 180 °C (Hoffmann, [38]). The popping sound starts off very slowly and quietly as the first few beans crack open and as more beans reach this point the noise will accelerate until it reaches a point from where it will begin to taper off. It can take up to 2 minutes for the first crack to begin and end, however, the higher the temperature at which roasting takes place, the shorter the first crack will be (Rao,[68]).

After the first crack, the roast can be stopped at any time because at this stage the coffee flavours develop. Despite still adding the same amount of heat to the roaster, the rate at which the coffee beans' temperature increase will have a noticeable decrease at this point. However, if not enough heat is added, the coffee beans will stop to roast and instead begin to bake, which will result in a poor-quality roast (Hoffmann, [38]).

4. Roast development

Once the first crack is reached the distinctive aroma attributed to coffee has developed. This development stage determines the roast degree and therefore bean colour of the end roast. The artisanal roaster is now in control of the balance between acidity and bitterness in the final product, for as the development continues the acid inside the beans are rapidly degrading as the bitterness of the bean start to increase (Hoffmann, [38]).

5. Second crack

As heating continues at the roasting temperature the coffee becomes darker and more rapid popping of coffee bean occurs as the carbon dioxide (CO_2) build up exceeds the strength of the cellulosic walls of the bean. This is called "second crack and usually occurs when roasting temperature overcome 200°C. At this stage, oils are driven to the surface of the beans and can be seen bubbling out of the bean pores. All the acidity has degraded, and a generic roast flavor has developed as a result of charring or burning. Therefore, when the second crack is reached, the quality of the coffee is of no concern for most of the characteristics of the raw coffee beans and intrinsic flavours developed during roasting has been lost, with the end product being high in body and bitterness (Hoffmann, [38]).

3.2.4. Roasting process control and the roast profile

During commercial roasting, the artisan roaster continuously evaluates the progression of the roast. This is done by continuously examining several parameters of the process as the roast progress through the above-mentioned stages (Hyed *et al.*, [36]). The artisan roaster interprets the observable parameters (such as bean colour, sound of first and second crack, and aroma formation) throughout the roast and compares it to the measured roast profile in order to determine necessary adjustments (increasing or decreasing air flow and air temperature) that should be made to achieve a specific end product quality (or degree of roast) (Hernández *et al.*, 2007).

Since most roasts will not exceed 20 minutes, these adjustment needs to be made almost instantaneously for the desired effect to happen. No set rules exist to produce a specific roast, and it takes years of learning and experience to be able to evaluate the roast and incorporate the correct adjustments to produce a superior quality product. Another objective in the control of the roasting process is to consistently reproduce the roast profile to obtain the same quality product when desired (Yeretzian *et al.*,[78]). Figure 2.3 illustrates a typical roast profile as it progresses through the above-mentioned stages. With most commercial coffee roasters equipped with thermocouples measuring the roast profile, the measuring of this temperature profile can quite easily be used in conjunction with a desired roast profile in a control strategy to achieve a perfect roast.

The roast profile is defined as the evolution of the bean-probe temperature as the roasting process progresses. Commercial roasters measure this temperature with a thermocouple inserted into the bean bed. This, however, is not to be confused or interpreted as the internal or surface temperatures of the bean, for it merely

measures the temperature of the medium surrounding it which, in this case, is a mixture of coffee beans and hot air (Rao,[68]; Schwartzberg, [70]).
The beginning temperature of the roast profile is the temperature of the hot air the moment the beans enter the drum and the immediate drop in temperature at the beginning of the roast profile, as illustrated in Figure 3.3, is just the logical interaction of beans at room temperature encountering an environment at a higher temperature (Rao,[68]).

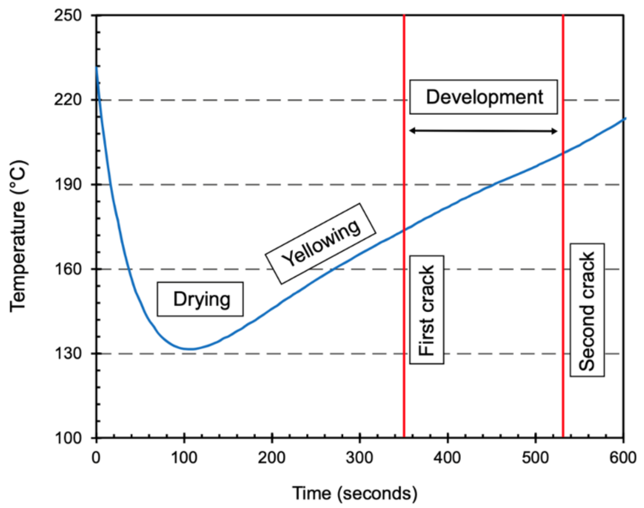


Figure 3.3: Typical roast profile (adapted from Rao, [68])

3.2.5. The degree of roast

After roasting is done, the quality of the roasted coffee needs to be evaluated and classified.
The condition of the final roasted coffee bean, as influenced by the various roasting conditions, is described as the degree of roast.
The degree of roast is normally based on the bean colour, though the exact roast level that each roast degree indicates is not agreed upon and can vary from roaster to roaster (Rao, [68]). The degree of roast can be determined in coffee roasting is categorized into the general light, medium, dark, and very dark roast (Wang & Lim, [77]). Table 3.3 gives a description of the various roast degrees in terms of the beans' progression through the roasting stages as well as their general appearance.

Table 3.3: Classification of roast degree (adapted from Hoffman, [38]).

Roast degree	Roast Progression	Appearance	General degree
Cinnamon roast	Extraction at the beginning of first crack	Light brown	Light roast
City roast	Extraction after first crack	Smoother surface due to expansion	Light roast
Full city roast	Extraction before second crack	Slight appearance of surface oils	Medium roast
Viennese roast	Extraction at the beginning of second crack	Noticeable presence of surface oils	Medium roast
French roast	Extraction during second crack	Dark brown and very oily	Dark roast
Italian roast	Extraction at the end of second crack	Dark brown almost burnt	Very dark roast

Over the years numerous research activities focused on the determination of the roast degree based on various physical properties of the roasted coffee, i.e. colour development of the bean, weight loss during the roasting process (more commonly referred to as roast loss), chemical composition of roasted beans and the final moisture content of the bean (Baggenstoss *et al.*, [2]; Wang & Lim, [77]).

It is found, however, that the composition of green coffee beans is highly dependent on various factors including cultivation climate, processing method, bean species and origin and the roasted beans are further dependent on the extent of roasting (Belitz *et al.*, [7]). Therefore, it is not seen as a suitable way to compare various compositions to obtain the roast degree.

3.3. Traditional roasting models

For the optimisation of the coffee roasting process, the temperature and moisture evolution in coffee beans during this process needs to be studied. In recent years, many researchers have focused on this by investigating the heat and mass transfer during the roasting of green coffee beans and proposing a model which can predict the temperature and moisture evolution within the beans.

3.3.1. Schwartzberg (2002) model

Schwartzberg [70] was the first to have developed a semi-physical model to predict the bean temperature and moisture content of the coffee bean during a batch roasting process, as well as the measured temperature of the batch of beans.
This model can be applied to different types of continuous and batch roaster.
The analysis of the process starts from the hot gas/air temperature, T_g.
It changes greatly in passing through a roaster. Therefore, changes in T_g in modelling roaster behaviour will be discussed first. Usually, only a fraction of the beans in a roaster are exposed to hot gas flow at a given time, and the change in bean temperature, T_b, is small during the passage of a small amount of gas. Neglecting gas-to-metal surface heat transfer, equation (3.1) is obtained.

$$GC_b \frac{dT_g}{dZ} = -h_{gb} \frac{dA_{gb}}{dZ} \left(T_g - T_b\right) \tag{3.1}$$

The temperature of the grain Tb is instead estimated as

$$\frac{dT_b}{dt} = \frac{GC_b(T_{gi}-T_{go})-Q_{gm}+Q_{mb}+Q_{eva}+Q_{react}}{m_{bd}(1-X)C_b} \tag{3.2}$$

Q_{gm} and Q_{mb} refer to heat transferred from gas-to-metal and metal-to-beans respectively. While Q_{eva} and Q_{react} was expressed as follows.

$$Q_{eva} = M_{bd} \Delta H_{eva} \frac{dX}{dt}$$
$$Q_{react} = \mathrm{A}e^{\left(\frac{H_a}{R(T_b+273{,}15)}\right)} \left(\frac{H_{et}-H_e}{H_{et}}\right) \tag{3.3}$$

Qreact is estimated on a semi-empirical basis.
In order to solve the overall balance (3.2), considering the terms (3.3), it is necessary to explain what the behavior fraction of water X present in the bean is during the roasting process. The mass balance for X proposed by Schwartzberg is

$$\frac{dX}{dt} = -\frac{4.32 \times 10^9 X^2}{d_b^2} e^{\left[\frac{-9889}{T_b+273,15}\right]} \tag{3.4}$$

This formula is also based on empirical data by Schwartzberg [70], assuming that:
1. Moisture loss was diffusively regulated.
2. The diffusion coefficient's temperature dependence was governed by an Arrhenius-type equation.
3. The driving rate for mass-transfer was proportional to X.
4. The diffusion coefficient was also proportional to X.
5. Although d_b variation was not tested, $-dX/dt$ was inversely proportional to d_b^2, where d_b is the effective bean diameter.
The term Qreact can also be written explicitly. Assuming that:
1. The rate of heat generation is proportional to the rate of reactions producing that heat.
2. The rates of these reactions are proportional to reactant concentration and to a coefficient governed by the Arrhenius equation.
3. Reactants are consumed in the reactions.
4. The concentrations of remaining reactants are proportional to $(H_{et} - H_e)/H_{et}$, where H_{et} is the total amount of reaction heat produced per kilogram of dry solids and H_e is the amount of heat produced thus far per kilogram of dry coffee.

Schwartzberg found that the simulated roast profile was in a good agreement with that of the experimental roast profile during the entire process, and that the largest difference in temperature between the simulated and experimental data was only 2 °C, measured by thermocouple (Ta).

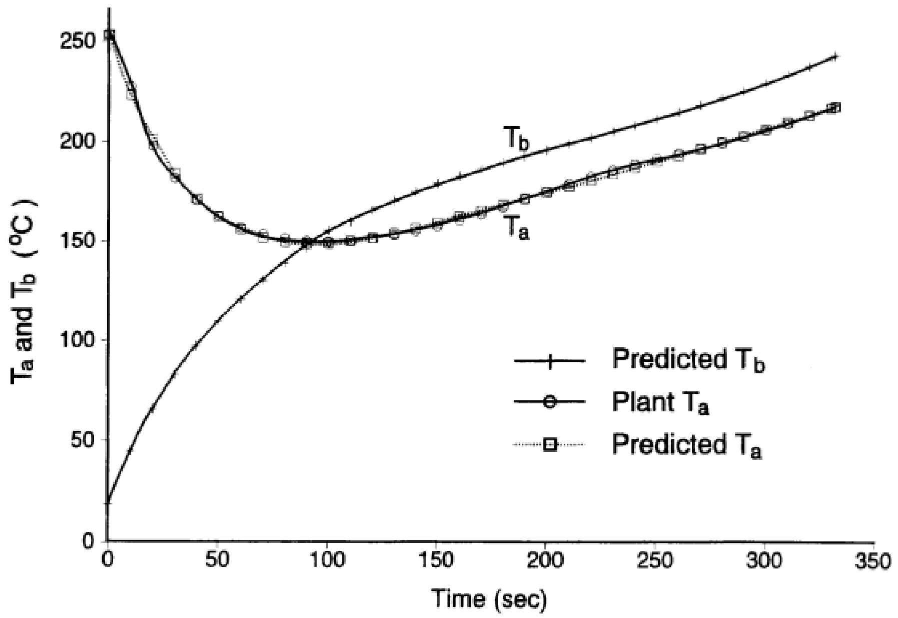


Figure 3.4: Experimental predicted Ta and predicted Tb vs time.

The final thermocouple temperature, at which the simulation was stopped, is 218°C reached in 332 seconds, corresponding to a beans temperature of 238°C.
Schwartzberg did not include any results obtained regarding the moisture loss of the green coffee beans during the roasting process, therefore the proposed equation for moisture loss could not be verified from his work.

3.3.2. Hernández et al. (2007) model

Hernandez et al., [34] performed an experimental and theoretical analysis of the heat and mass transfer to evaluate the coffee bean's temperature and moisture content during the roasting in a batch system at different temperatures (190°C, 240°C and 300°C).
The mathematical reference model used is given by Schwartzberg [70] with different starting of X and Tb.
The results obtained are in line with the experimental ones.
Unlike Schwartzberg, Hernandez et al., [34] does not stop the simulation at Tb=238° C. This allowed him to observe that, in case of T_{air} at 300°C, after 90s the optimal bean's temperature reach 240° C, the exothermic reactions responsible of the aroma

and flavor are reduced and the beans begin to burn. This phenomenon described by Hernandez was called over-roasting.
Also the moisture content simulation, using eq. (3.4) gave to Hernandez et al., [34] acceptable results until the 300 seconds of simulation.
After that the model significantly underestimates the water content. The trend of experimental data is linear over time while from the Hernandez model it isn't.

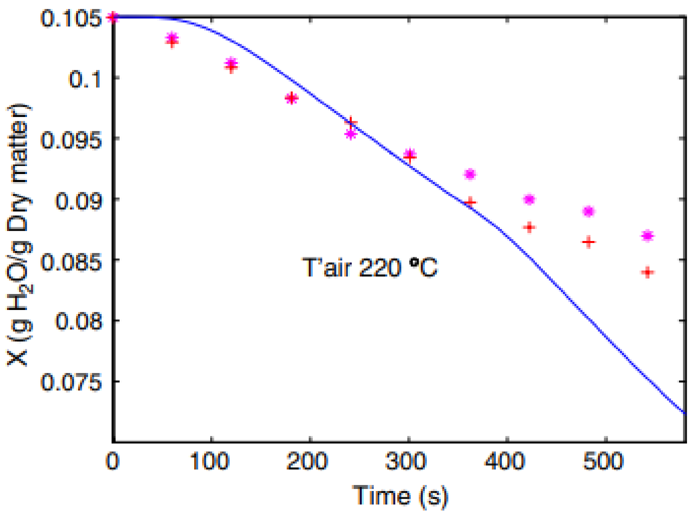


Figure 3.5: Evolution of the bean's moisture content (*, +: experimental, -: simulated)

Hernandez et al., [34] observed that experimentally after 300 s of roasting the heat transfer is very low. So, to obtain 2% of moisture is necessary to increase the roasting time.

3.3.3. Bottazzi et al. (2011)

The coffee process model proposed by Bottazzi et al., [11] starts from the balance on the bean in equation (3.5). This equation is based on Schwartzberg equation (3.2) neglecting the heat transferred from gas-to-metal and from metal-to-beans.

$$\frac{\partial T_b}{\partial t} = \frac{Q_{gb} + \left(Q_{react} + m_{bd} \Delta H_{eva} \left(\frac{dX_b}{dt}\right)\right)}{m_{bd}(1+X_b)C_b} \tag{3.5}$$

Bottazzi et al., [11] estimated the thermal power Q_{gb} transferred from hot air to beans as:

$$Q_{gb} = h_{gb} A_{gb} \left(T_{gi} - T_b\right) \tag{3.6}$$

To evaluate the model, Bottazzi at al., [11] performed two different roasting cycles: a high-temperature short roasting process (HTST), where the inlet hot air temperature T_{gi} was equal to 533 K, and a low-temperature long process (LTLT) with T_{gi} setted at 493 K. the experiment is conducted under isothermal conditions. The temperature checked by Bottazzi are the bean core temperature, the bean pile temperature and the numerical bean temperature. The results obtained fit the experimental ones quite well, although with evident differences in the two cases.
In the LTLT process the bean core temperature and the bean pile temperature have a difference of a few degrees in the first 180 seconds and then equal until the end of the roasting. The numerical bean temperature at 180 seconds seem to be the average between the two values and then grow to reach the stationary temperature equal to that of the incoming air. The total roasting time for LTLT process is 720 seconds with a final numerical temperature of 493 K.
Instead, in the HTLT process the bean core temperature and the bean pile temperature are quite different after 150 seconds of roasting. The numerical bean temperature has a trend very similar to that the bean pile temperature until the 150 seconds of roasting. After that, the numerical temperature increase reaching the stationary temperature of air. The total roasting time for HTLT process is 300 seconds with a final numerical temperature of 523 K. In both case the final numerical temperature is always higher than bean and pile temperature.
The moisture content is estimated by Bottazzi et al., [11] using the equation (3.4). The values obtained are given for the two cases treated by Bottazzi et al., [11]:

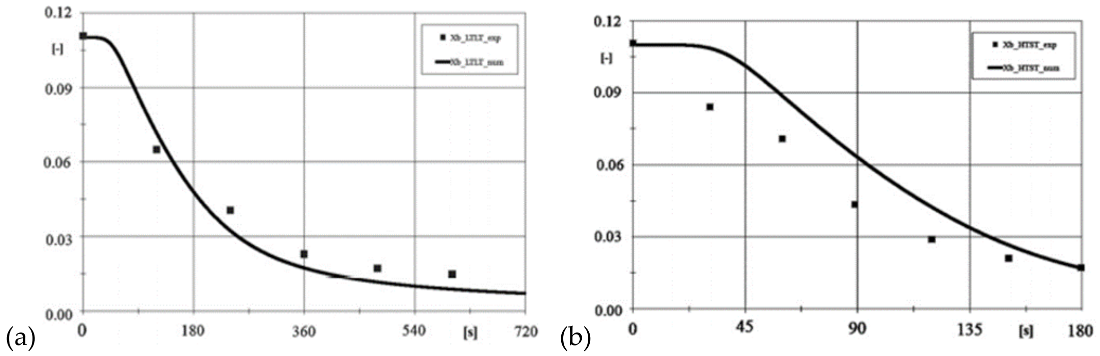


Figure 3.6: Bean moisture content from experimental data (dots) and from numerical results (continuous line) for (a) the LTLT process and (b) the HTST process.

Considering the HTST case, the numerical error is larger than in the LTLT case, particularly in the first part of the roasting cycle. The model, according to Bottazzi et al., [11] overestimated the initial time needed to start the evaporation process and further investigation is needed to improve the model's response to the fast transients. Thus, the predictive capability of the proposed model is more accurate when considering a long roasting process rather than a fast-roasting cycle both for non-rotating and rotating batch machines.

3.3.4. Alonso Torres et al. (2013)

Alonso Torres et al., [1] estimate heat and mass transfer in individual coffee beans during roasting using computational fluid dynamics (CFD). To experimentally validate the numerical model, Alonso Torres et al., [1] studied a single coffee bean in a cylindrical glass tube roasted by a hot air flow, using the identical geometrical 3D configuration and hot air flow conditions as the ones used for numerical simulations. Then, temperature and humidity calculations obtained with the model were compared with experimental data. The equations model adopted by Alonso Torres et al., [1] are equations (3.2), (3.3) and (3.4) given by Schwartzberg [70].
A comparison of coffee bean surface temperature (experimental) with the one obtained using the CFD simulation without heat loss due to the equipment and surrounding for roasting temperatures of 473 K (200 °C) and 523 K (250 °C) is made. At the lower temperatures (473 K, 200 °C), a better match between the experimental results and the corresponding simulation were obtained, while by increasing roasting temperatures the simulation becomes slightly less accurate. Alonso Torres

et al., [1] thinks this behavior is due to the increase in temperature (>503 K, 230 °C) when coffee beans experience exothermic chemical reactions and carbonization reactions are initiated. For moisture content analysis, Alonso Torres et. al., [1] compared the CFD simulation with experimental data from Schenker et al., [71]. Agreement was found between the two curves since the trend on the curves is the same. At a roasting time of 300 seconds there is a difference of about 1g H2O/100 g on a wet basis. Alonso Torres et al., [1] attributes this difference to the model's lack of humidity in the roasting air.

3.3.5. Fabbri et al. (2011) model

Fabbri et al. [29] aimed to develop a numerical model, capable of simulating the heat and moisture transfer that takes place inside a coffee bean during the roasting process based on a three-dimensional digitised geometry. The digitised geometry used by the proposed model was constructed by means of a three-dimensional scan of a green coffee bean. This study is conducted on a rotating cylindrical roaster in natural convection conditions.

To model the bean temperature, Fabbri et al. [29] assumed that the heat transfer that takes place during roasting is predominantly convection, from hot roasting air to the surface of the coffee bean, and conduction, that occurs from the surface of the bean towards its core. Equation (3.7) is proposed to model the heat transfer by conduction that takes place inside the bean, while a boundary condition is offered to represent the convection that occurs between the roasting air and the surface of the bean (Fabbri et al., [29]).

$$\rho_b C_b \frac{\partial T_b}{\partial t} + \nabla(-k_b \nabla T_b) = 0 \tag{3.7}$$

Where k_b and C_b refer to bean conductivity and bean specific heat respectively. The proposed heat transfer model neglects any heat that may be produced during roasting by exothermic roasting reactions, and only accounts for heat transferred from the hot roasting air. The initial temperature of the bean was considered uniform (298 K) while the boundary condition imposed on the interface between the surface of the bean and the air, was convective (heat flux):

$$-nq = h(T_\infty - T) + q0 \quad (3.8)$$

being T_∞ the external bulk temperature and n the directional vector. The value of q and q0 were calculated by the following equations

$$q = -k\nabla T$$

$$q0 = -\Delta H_{eva} D_{ws} \nabla c \quad (3.9)$$

D_{ws} is the surface mass diffusivity of water and c the water content in the bean.
For mass transfer, Fabbri et al. [29] assumed that the moisture inside the coffee bean will diffuse toward the surface and that only at the surface of the bean, the moisture will start to evaporate, while the mass transfer that takes place during roasting was assumed to be governed by Fick's law. The proposed moisture loss model, in terms of the moisture concentration inside the bean, is given by

$$\frac{\partial c_w}{\partial t} + \nabla(D_w \nabla c_w) = 0 \quad (3.10)$$

with D_w is the water mass diffusivity in the bean. On the interface between the surface of the bean and the air, a flux condition was imposed

$$n(D_w \nabla c_w) = k_w(c_b - c) \quad (3.11)$$

According to Fick's law of diffusion, the mass flux of the diffusant is directly proportional to the gradient of concentration and the proportionality constant is the diffusion coefficient. Therefore, the diffusion coefficient used is of great importance for the accuracy of the proposed model.
To validate the proposed model, Fabbri et al. [29] used a rotating drum prototype to roast green coffee beans at an air temperature of 200 °C. Fabbri et al. [29] found that the simulated and experimental bean temperature (which was obtained from five replicate roasts) compared very well with one another with a root mean square error (RMSE) of 5.97 °C.

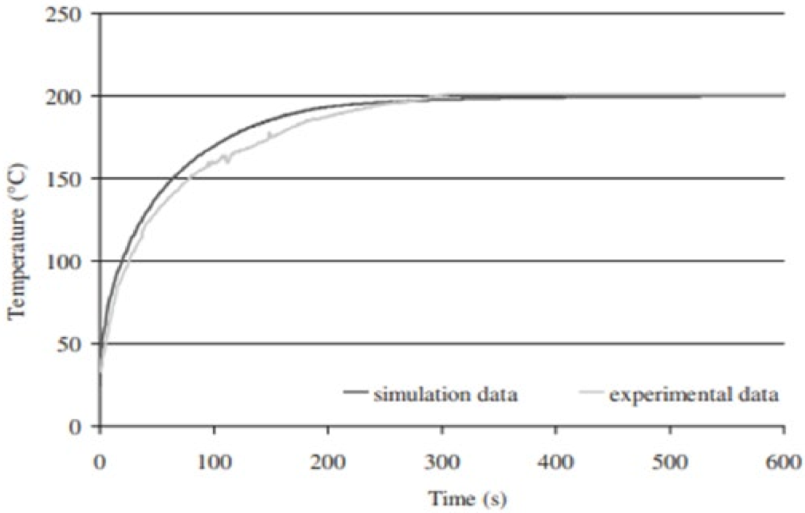


Figure 3.7: The calculated (black) and observed (gray) time–temperature curves for a point located at a depth of 3 mm from the surface.

For moisture content, a RMSE of 0.75 % was obtained from the compared results, showing that they appear to be in good agreement. According to Fabbri et al. [29], the slight deviation between simulated and experimental results that can be observed at certain points may be due to steam produced inside the coffee bean when the bean temperature increases. Also in this case the simulated and experimental moisture values appear to be in good agreement (RMSE 264.251 mol/m3). The maximum standard deviation in the observed data (±39 mol/m3) occurs at time 8 min, even if it is very small.

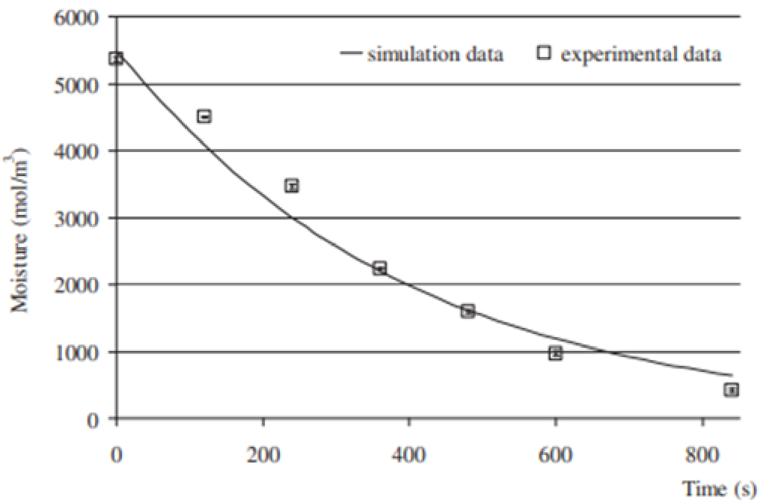


Figure 3.8: The simulated and experimental moisture concentration at different treatment time.

Despite these deviations, Fabbri et al. [29] maintained that the proposed model predicted the moisture content of coffee beans during roasting more accurately than those proposed by Schwartzberg [70].

3.3.6. Hyed et al. (2007) model

Hyed et al., [36] developed a roasting model for bean heat and mass transfer in a spouted bed roaster. Like Fabbri et al., [29], Hyed et al., [36] focused on the dynamics of transport phenomena inside the grain considering that temperature and moisture content are not homogeneous.

$$\rho_{bd}(C_{bd} - XC_w)\frac{\partial T_b(r,t)}{\partial t} = k_b\left(\frac{\partial^2 T}{\partial^2 r} + \frac{2}{r}\frac{\partial T}{\partial r}\right) \tag{3.12}$$

At coffee bean surface r=Rb and the Hyed et al., [36] equation became

$$-k_b\frac{\partial T_b}{\partial t} = h_{gb}(T_b - T_g) + k_w(c_{sb} - c_g)\Delta H_{eva} \tag{3.13}$$

Hyed et al., [36] performed a comparison between experimental data and simulated data for two different values of T air inlet 210°C and 250° C

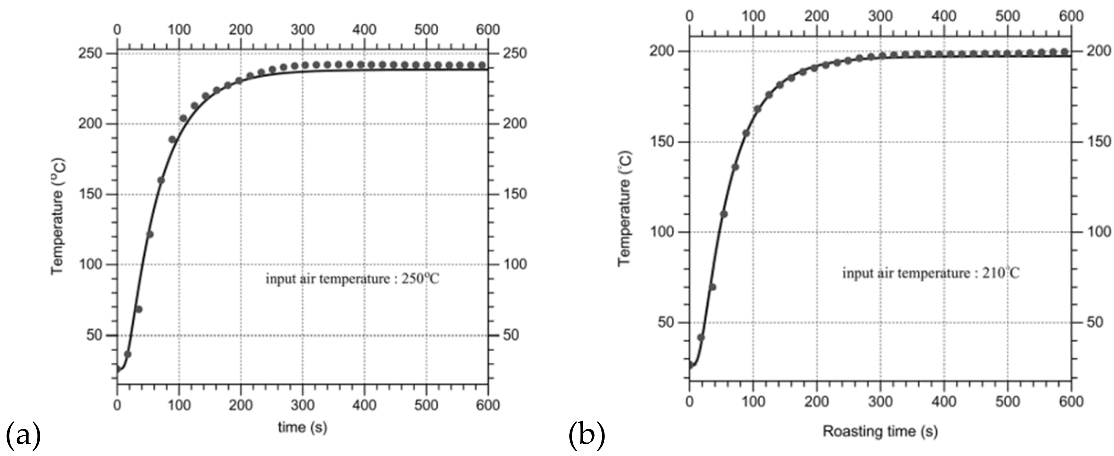
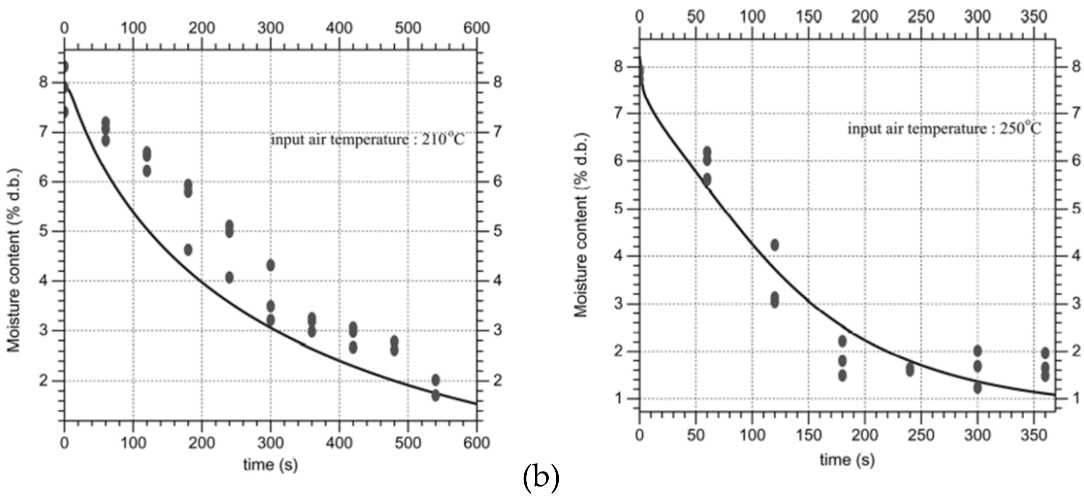


Figure 3.9: Comparison of experimental (•) and simulated (-) bean internal temperature during roasting at 250°C (a) and 210°C (b).

The main problem is to approximate bean internal temperature, which is closely related with final product quality. Hyed et al., [36] found a small distortion, between 240 and 300 s of roasting process at 250 C, when experimental bean internal temperature was increased again. This phenomenon could occur as a consequence of the exothermic pyrolytic reactions, which are not taken into account in the Hyed et al., [36] model.

Figure 3.14 illustrate that moisture content was well simulated, in comparison with experimental data obtained for three replicates.



(a) (b)

Figure 3.10: Comparison of experimental (•) and simulated (-) bean moisture content during roasting at 210°C (a) and at 250°C (b).

However, the modeling of moisture content proposed by Hyed et al., [36] does not take into account all the physical phenomena that can occur (e.g., formation of water during pyrolytic reactions, formation of steam inside the bean when the internal temperature is high, and influence of temperature on the apparent water diffusivity).

4 Roasting problem definition

As mentioned in chapter 2, the process industry, including the food industry, is increasingly bound to environmental and sustainability aspects. All the activities performed along the coffee supply chain can be made more sustainable. Coffee farming can be made more sustainable by using organic fertilizers with a less intensive approach to cultivation. The coffee grounds and waste from the industrial process can be used as excellent fertilizers, rich in nutrients, allowing a circular economy to be generated where the finished product is part of the product's life cycle. The transport of the product, instead, is strictly limited to the distances to be covered and to the use of vehicles, making sustainable initiatives more complicated. For this reason the LCA previously performed is logistic free.

The activity that allows the greatest margin for intervention in technological terms towards a reduction of environmental impact is certainly the roasting and drying process.

The purpose of this work is to propose and evaluate the use of energy or renewable energy sources with lower environmental impact as a replacement for natural gas or LPG while maintaining or improving the quality of final product.

In order to acquire the best quality roasted coffee, an accurate real-time estimation and prediction model are required for the roasting process. From this, the optimum roasting procedure can be derived and further controlled to deliver a reproducible high-quality product.

In order to obtain this model, the temperature and moisture development during the roasting process needs to be quantified and further related to the degree of roast. The models that will be analysed will therefore have to take into account the final temperature of the beans as well as the time required to take coffee up to 240°C.

Among the possible sustainable resources, the solar energy, discussed in this chapter, result to be a good option to perform roasting.

4.1. Solar energy

Solar energy is the energy associated with solar radiation and is the primary source of energy on Earth. Solar radiation is nothing more than electromagnetic radiation of varying frequencies propagating through space. The total amount of energy radiation emitted by the Sun in the unit time and area measured at the outer thresholds of the Earth's atmosphere, on a plane perpendicular to the sun's rays, is called the solar constant. It is equal to 1367 W/m2. However, the power that reaches the inner thresholds of the Earth's atmosphere is much lower. There are two explanations for this: the first is that the sun's rays are only perpendicular to the earth's surface in certain areas and zones, and only in these cases 1367 W/m^2 is measured on the outer atmospheric surface. The second is that solar radiation is scattered and reflected as it passes through the atmosphere.
The maximum effective power per area reaching the Earth’s Sea level, that can be measured, is approximately 1000 W/m^2 while the average amount of solar energy received at Earth's atmosphere is around 342 W/m^2, of which about 30% is scattered or reflected to space, leaving about 70% (239 W/m^2) available for harvesting and capture.
In order to generate electricity or heat from solar energy, the latter must be converted or concentrated through specific equipment such as photovoltaic (PV) panels or solar concentrators (SC). In our case, where we need to convert solar radiation into heat, solar concentrators should be used and evaluated.

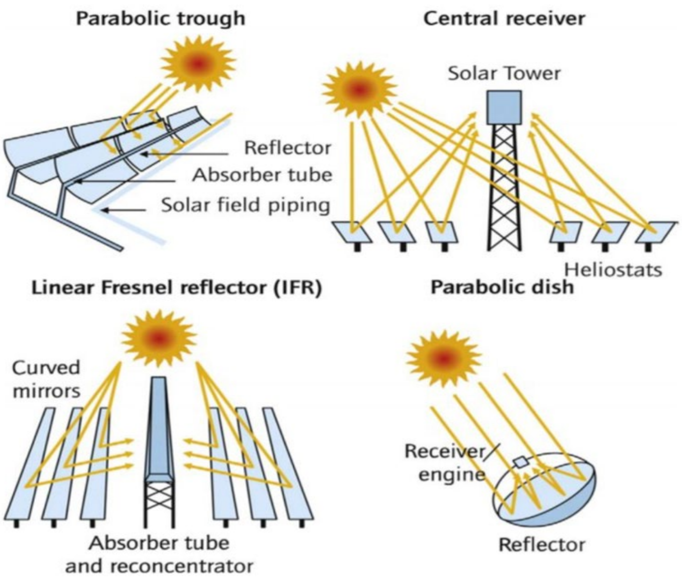


Figure 4.1: Main type of solar concentrators.

According to the geometry of the solar collectors it is possible to identify different systems (Figure 4.1): parabolic discs, central tower, linear parabolic collectors (or cylinder-parabolic) and, variant of the latter, with linear mirror collectors by Fresnel.

Parabolic plate solar systems use parabolic reflective panels that follow the movement of the sun by rotating on two axes and concentrate solar radiation on a receiver placed in the focal point. The receiver can consist of a Stirling motor with electric generator.

In central tower systems the solar field consists of a large number of flat reflective panels that individually chase the movement of the sun, each one rotating on two axes, to concentrate solar radiation on a single receiver mounted on the top of a tower. The solar field is the equivalent of a huge parabolic surface, with very high concentration factors. A fluid circulating through the receiver removes the collected heat.

In systems with linear parabolic collectors, the concentrator has an open cylinder-shaped surface with a parabolic profile instead of a circular one. The collectors "chase" the sun rotating on a single axis; the radiation is conveyed on the receiver tube placed in the focal axis of the cylinder; inside the receiver tube flows a heat transfer fluid that collects thermal energy and transfers it to the system of electrical generation or heat accumulation.

In systems with Fresnel mirror linear collectors the concentrator consists of segments of flat mirrors arranged according to the principle of the Fresnel lens, with the receiver tube positioned in the focal axis. The rotation for solar tracking concerns only the segments of the concentrator, while the receiver tube and the support structure remain fixed. Compared to linear parabolic collectors this system has lower performance (the total annual yield is about 60% of that obtained with linear parabolic collectors) but the plant costs are lower because the receiver tube is fixed, does not require expensive mobile joints, and can use high pressure fluids, such as steam. The mirror rotation system is simpler, and the supporting structures require less material.

The thermal power of a solar concentrator (ϕ) is the most important parameter for sizing this system.

It is the product of the following factors: the density of solar radiation at sea level (δ); the opening of the solar collector which helps to concentrate the radiation (A_c); the reflectivity of the solar collector (γ_c), which depends on the materials of the collector and the precision with which the surface is machined; the absorption coefficient of the receiver (α_r), which is clearly greater if this is painted with appropriate black paints.

For large professional solar concentrators - those used to produce hot water and electricity - the heat output does not exceed approximately 0.4-0.7 kW per square meter collector opening considering that only a fraction ϵ of the total solar density is direct on the concentrator. So, the formula (2.14) can be used for a quick estimation of the required collector surface

$$\Phi = \epsilon * \delta * A_c * \gamma_c * \alpha_r \tag{4.1}$$

The density of solar radiation δ varies during the day and from latitudine to latitudine.

In Italy, the mean annual solar radiation ranges from 3,6 kWh/m^{2}day in Po river plain area, to 5,4 kWh/m^{2}day in Sicily (ENI). For an annual average of sunny hours per day of 6, these values correspond to a range of 600-900 W/m^2.

It can be considered with a good approximation that the average solar density in Italy is 750 W/m^2.
As the size of the collector increases, the amount of energy intercepted increases but on the other hand, if all other factors remain constant, also increases the heat loss especially by the receiver, which is linked to the temperature of the latter.
The sum of the energy intercepted by the collector and the heat loss from the system (reach a maximum at a certain optimal value of the opening of the collector, that is in practice the diameter of the disc if it is a parabolic collector. This is the key point for sizing the solar concentrator. Note that heat loss is also a function of the design of the concentrator, so it may be useful - at the design stage - to compare different designs.

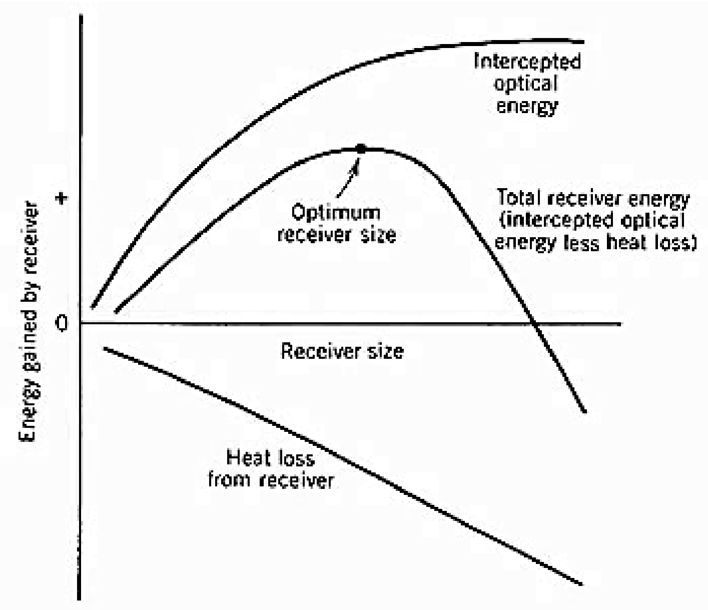


Figure 4.2: Optimization of receiver size (from Consulente-energia [19]).

On a practical level, in the last decade some companies or new start-ups have started coffee roasting processes with solar concentrator plants.
In Italy, PuroSole [66] has developed a technique of coffee roasting by solar radiation, an innovative way to replace with solar energy the exploitation of non-renewable natural resources and reduce the resulting environmental pollution. The idea behind this technique is to induce the roasting of the raw coffee beans, instead of contact with hot air, as currently in use, by direct solar radiation, or more precisely not with the heat of the sun, but with the direct irradiation of its light rays.

This means that it is no longer necessary burn fuel to obtain the necessary heat. By using the heat induced by the sun, this system is more eco-sustainable than any other classic roasting method used to date. Every 1000 kg of coffee roasted with the sun must not burn more than 200 cubic meters of methane of classical roasting, thus avoiding the production and release into the atmosphere of more than 400 kg of CO_2.

Decrease the emission in atmosphere is not the only advantage of roasting coffee with direct solar energy compared to hot air. The peculiarity of roasting by sunlight radiation consists in a better uniformity of the degree of roasting between the outside and the inside of the bean and a greater preservation of its natural properties with consequent exaltation of its organoleptic characteristics (PuroSole, Technology [66]). This is because the solar roasting allows to obtain evenly roasted grains in a short time compared to the traditional techniques described above, also eliminating the need for a forced convection of the air.

The method of roasting by sunlight radiation, is based essentially on the heating of coffee beans through the electromagnetic energy of the light emanating from the sun.

The raw coffee bean is light green and partially translucent, or not completely opaque to the light and when illuminated from the outside the light penetrates inside the grain from which it is absorbed and converted into heat at different depths as a function of the wavelength. Sunlight has a special feature that is practically not reproducible by any type of artificial light generator: it has a very wide color spectrum. This means that it contains all the different wavelengths, from the ultraviolet range to the infrared range.

This aspect makes that the heat is "generated" inside the coffee grain simultaneously at different depths and not only propagated from the outside to the inside as is the case with traditional heating in contact with hot air. The photons that penetrate the surface of the coffee grain, give energy during their journey in a different way depending on both their frequency and the colour of the bean, and that in turn changes with the degree of roasting.

Moreover, in this technique, the function of air is even opposite to the traditional one. The air that envelops the grain, not being heated by the sun’s rays by virtue of its transparency, will always be colder than the beans itself, thus counteracting the rise in temperature on the surface of the coffee beans and contributing to the reduction of the temperature gradient between the outside and the inside of the bean itself.

The fast and uniform roasting that solar radiation facilitates, is undoubtedly one of the advantages of this roasting technique. But it is not the only one: in fact, the other important aspect is the absence of forced air convection on the coffee bean. In traditional systems of roasting both fluid bed and rotating drum, the air is forced to circulate between the coffee beans as the only carrier of heat between the gas burner, which generates the thermal energy, and the coffee, which must absorb it. Once the high-temperature air (300-400° C) has been in direct contact with the coffee bean, it cools giving its heat to the bean and must be replaced by a new hot air flow. For this reason, air is always kept in circulation. The forced circulation, however, also takes away the aerial products of the physical transformation that takes place in the beans. In roasting by radiation, on the contrary, the grain is always surrounded by its own vapors produced by the processing of oils and sugars; transformations that are a consequence of the chemical reaction induced by the heat generated inside the grain itself by light radiation.

As we can therefore expect, this different roasting technique produces different organoleptic results. The chemical analysis of roasted bean and therefore of its flavour, is quite complex, as for the traditional roasting, this because of the hundreds of different chemical reactions that take place during the process. However, a subjective analysis based on double blind comparisons, were performed by a small group of volunteers on the same raw coffee mono origin (Santos - Brazil) roasted both by classic roasters and by innovative PuroSole's plant [66]. In 100% of comparisons, the evaluation of solar roasting has always been considered superior to the traditional one in reference to the parameters of: aroma, acidity, aftertaste, body and creaminess. Even if the analysis is biased the results confirm the expected superior quality of solar roasted coffee compared to traditional one.

Nevertheless, this type of roasting approach has an important limit. The most delicate aspect of the physics of this process is given by the extreme directionality of the light. To properly roast the coffee, during the entire cooking phase, each bean must be directly illuminated by the different angles cyclically and at the same time without staying too exposed to the intense light from the same angle for too long.

In fact, the temperature of a coffee bean exposed to this intensity of light can rise by almost 10 ºC per second.
In contrast to the classic hot air heating process, which penetrates and circulates in any free space between the beans during roasting, the light will only hit the coffee beans in front of it, that naturally cover the beans behind leaving them in the shade. It should be noted that the energy for roasting, in this technique, cannot reach the coffee in any other way: if a bean is not irradiated directly it will remain almost completely raw even if immersed together with perfectly roasted coffee.
Another aspect to consider, that requires a special organization, is linked to the discontinuity of the availability of solar energy itself. Due to its peculiarity, the concentrated roasting system requires a constant solar illumination throughout the roasting phase. This aspect unfortunately limits the use of this technique to the only days when it is predictable, with a good reliability, a clear sky in which the sun is not covered by clouds too often. It is in fact very important that, once the roasting process has started, it is not interrupted in the next 5-20 minutes.
The process of raising the temperature of the coffee in roasting must be kept under control and comply with the maximum tolerances allowed by its roasting profile. This limitation is the main critical aspect of this roasting technique and has a significant influence on the times, days, and places where it can be applied. Fortunately, this critical aspect can be contained by the capacity of coffee, both raw and roasted, to be stored for long periods in silos. A careful seasonal planning according to the place where the plant is installed, will allow to obtain a good productivity.
Finally, unlike what it may seem, the intensity of solar radiation in winter is not very different from what you have in summer. The difference is only in the different inclination with which the radiation reaches the ground and the number of daily hours in which it is usable. This is just to underline that, apart from the different hourly productivity between the months of the year, there are no substantial differences in the result quality.

5 Traditional roasting model

As mentioned in previous chapter, roasting is the most significant step throughout coffee transformation process, in determining final quality and organoleptic properties of coffee.

There are no set rules to run this process and also the dynamic processes taking place in the individual bean are still little understood.

Despite that many variables can potentially be monitored in order to control the process and obtain the desired characteristics.

These include the bean temperature, the colour, the weight/mass loss, the odour, the chemical composition and more. Among all these, three are of particular importance for a better understanding and optimization of the coffee roasting process, as they form the basis of most of the chemical and physical transformations and reactions taking place inside the coffee beans. These are the bean temperature and moisture content as well as the roasting gas temperature.

A good control of the hot air temperature and roasting time can guarantee constant final product quality, provided that green coffee beans quality does not vary.

To evaluate alternative models for a sustainable solar-powered roasting, it is firstly necessary understand the traditional process and the impact of the main variables on it.

Several models (with one succession and improvement on the other) have been developed, analyzed and evaluated to investigate and predict the effect of temperature on the coffee bean roasting profile with regard to the heat and mass transfer during roasting of green coffee bean.

For greater accuracy of the roasting chamber models, each application requires ad hoc identification of the model parameters for its design and testing, so it would have been necessary to proceed with several laboratory activities.

Since the experimental study process was not possible, it was proceeded with bibliographic research to establish what are the fundamental quantities values of coffee beans and the principal equation that run the process.

In this Chapter traditional roasting is analysed providing a process index to describe the relationship between the main parameters of the process and a simplified model of bean's temperature and moisture profile is defined as well.

5.1. Process index definition

The process index (PI) is a constant parameter able to describe the relationship between the main variables parameters of the process. At an industrial level it is a useful indicator to make a scale up from a laboratory batch to a production plant.

The PI can be derived from a simplified heat transfer balance on beans that can take into account only the contribution of hot gases, neglecting moisture evaporation and exothermic heat generation.:

$$m_b\, C_b \frac{dT_b}{dt} = G\, C_g (T_{gi} - T_{go}) \tag{5.1}$$

Integrating it, you get

$$m_b C_b \left(T_{bf} - T_{bi}\right) = G C_g (T_{gi} - T_{go}) t_R \tag{5.2}$$

where G is the gas mass-flow rate, C_g and C_b are the specific heat capacity of drying air and bean respectively, t_R is the roasting time and T_{bf} and T_{bi} are inlet and outlet beans temperatures fixed by the producer.

The deltaT air can be estimated starting from the energy balance (3.1), that integrated gives

$$T_{gi} - T_{go} = \left(T_{gi} - T_b\right)\left(1 - e^{-\left(\frac{h_{gb} A_{gb}}{G C_g}\right)}\right) \tag{5.3}$$

where h_{gb} is the heat transfer coefficient as function of gas/air velocity, A_{ag} is the air to beans heat transfer area and T_b can be approximated as the average temperature of the beans. The heat is mainly transferred from the gas to the beans by convection while a small part is transferred from the gas to the metal of the chamber which in turn transfers heat to the beans by conduction. Although all types of heat transfer, convection is most effective and most appropriate for uniform roasting. Thus, for the sake of simplicity, it is the only heat contribution considered in the previous equation.

Rearranging the terms in (5.3) the process index is defined

$$PI = \frac{Gt_R}{m_b} = \frac{C_b(T_{bf}-T_{bi})}{C_g(T_{gi}-T_{go})} \tag{5.4}$$

Depending on the specific temperatures chosen by the manufacturer, which are linked to the size of the batches to be roasted and the final desired quality of the product, each process has its own process index.
It is good to remember that it is a reliable constant but still based on different approximations.

5.1.1. Sensitivity analysis

The process index defined has three degree of freedom, this allow to have an estimation of one variables parameters once the others are fixed.
At fixed roasting time, the hot gas flow rate increase quite linearly with beans mass loaded since the hot gas provide the heat necessary to rise beans temperature. (Figure 5.1). Higher is the quantity of coffee to be roasted higher will be the gas flow rate at the inlet of the roasting chamber. Alternatively, if the gas flow rate is stated, to guarantee a complete roasting of the coffee beans loaded, the roasting time increase, also in this case quite linearly, with the beans mass. (Figure 5.3).
Instead an exponential trend link the roasting time and the hot gas flow rate. The roasting time decrease significantly with the increase of the gas flow (Figure 5.2). This can be explained by the fact that high quantity of heat is required at the beginning of the process to start water evaporation and all the chemical transformations that takes place during roasting thus, very low gas flow rate are not an optimal solution to roast high quality of coffee.

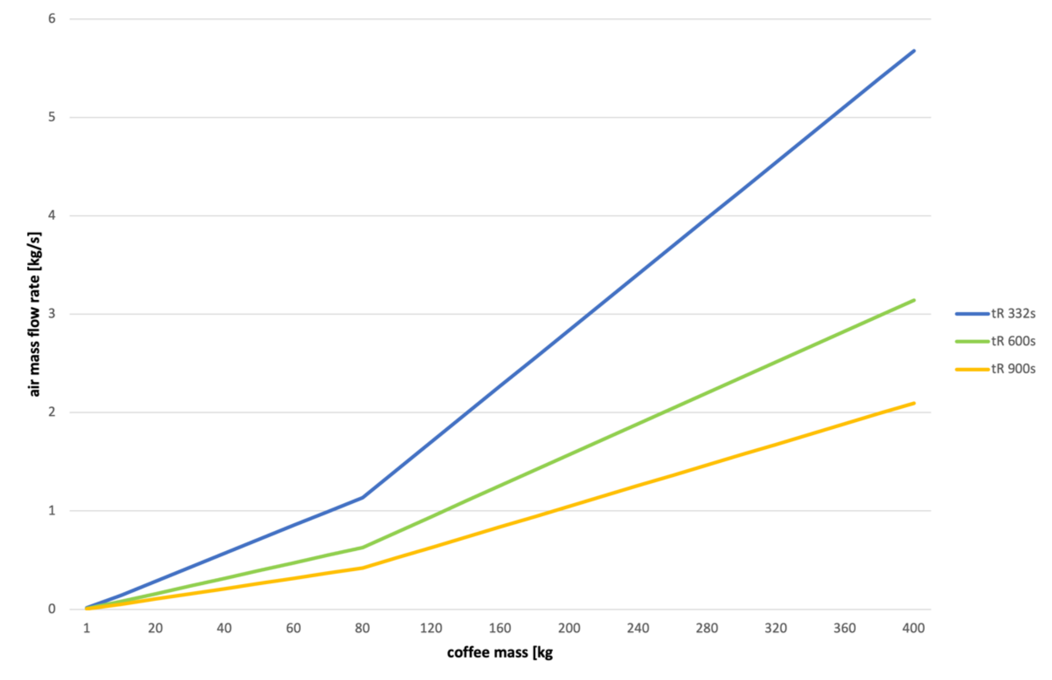


Figure 5.1: G variation compared to different amounts of coffee to be roasted in different roasting times (5,10 and 15 min)

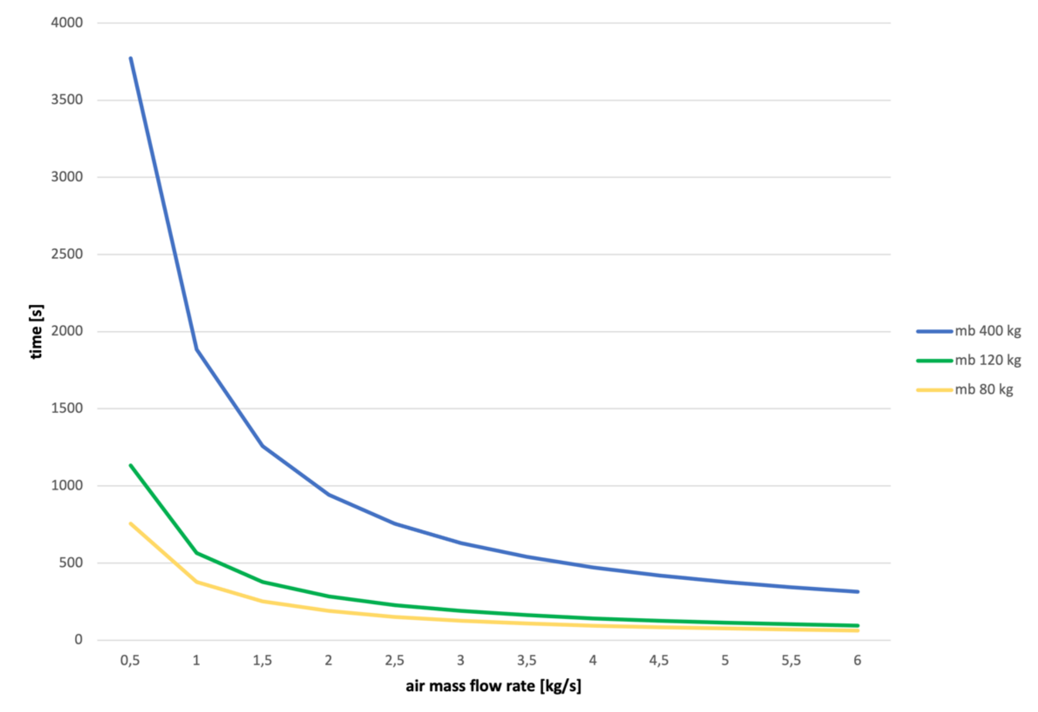


Figure 5.2: Variation of roasting time depending on the mass air flow rate used for different process batches.

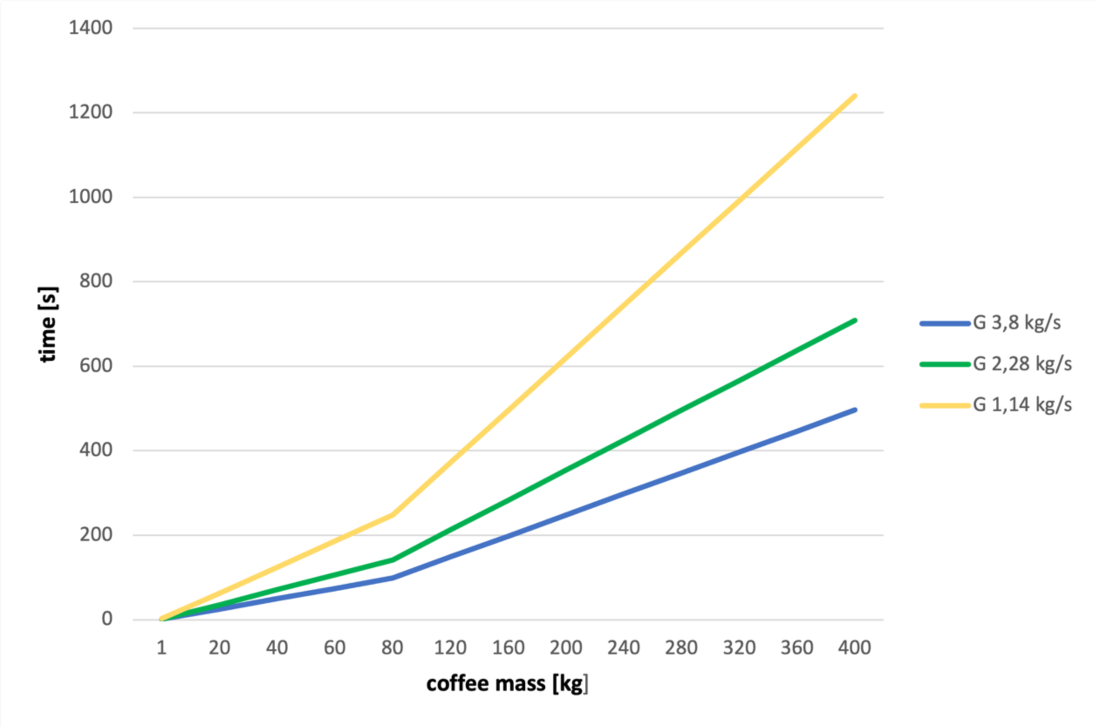


Figure 5.3: Variation of roasting time depending on the mass bean loaded at different G.

The main limit of this analysis is that the air inlet temperature is fixed at 300°C, that is a high value compared to the T_{gi} used in most of the roasting model proposed in literature.

Moreover, the hot gas temperature has a significant impact on the required flow rate and consequently on the time necessary to roast.

It's possible to highlight the relationship between roasting time and $T_{gi.}$ using the following equation

$$ln\frac{T_{gi}-T_{bi}}{T_{gi}-T_{bf}} = \frac{GC_g t_R}{m_b C_b}\left(1 - e^{-\left(\frac{h_{gb}A_{gb}}{GC_g}\right)}\right) \quad (5.5)$$

obtained substituting the equation (5.3) in (5.1) and integrating it.

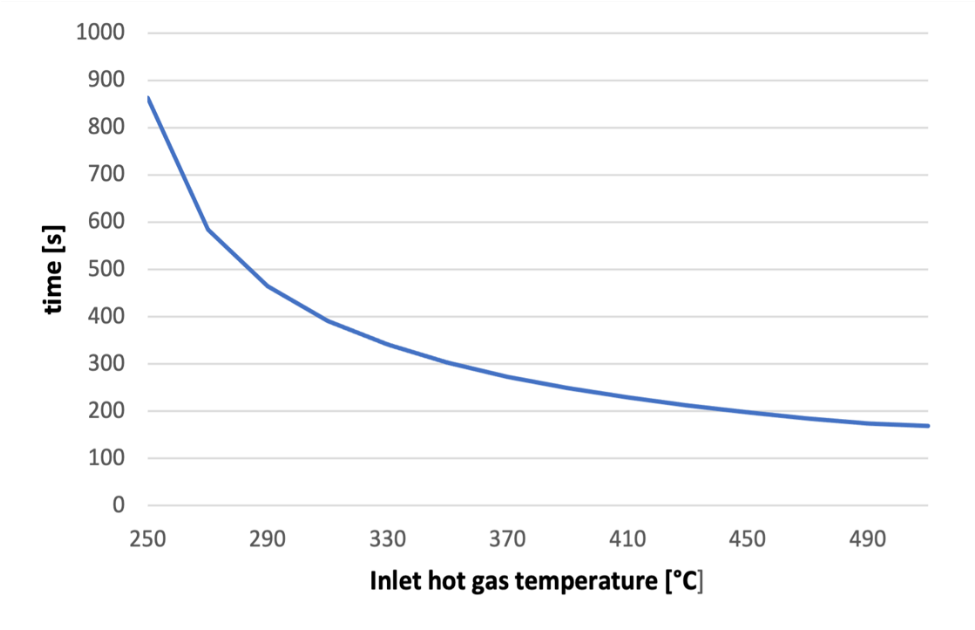


Figure 5.4: Variation of roasting time depending on inlet gas temperature.

The final beans temperature T_{bF} is strictly related to the inlet temperature of the hot gases, which set a limit to maximum roasting temperature the bean could reach, and the desired quality to obtain.

A complete roasting is achieved after the second crack at T_b=240°C and before the bean start burning. Thus, the Tgi considered in Figure 5.4 start from to 250°C in order to guarantee the second crack. As expected a strong influence of the gas temperature on the roasting time is shown. An optimal choice of the roasting temperature is therefore recommended to reduce the process as much as possible.

5.2. Traditional roasting's profiles

The control of the coffee beans temperature and moisture content has a key role in the roasting process (Vosloo et al., [75]). Hence, heat and mass transfer during roasting need to be deeply investigated.

The model proposed is based on the following assumptions:

1. The heat transfer phenomena considered is only the convection from air mass flow rate to the beans, neglecting the heat transfer from air to metal and the heat transfer from metal parts to beans
2. The air temperature is kept constant
3. Coffee beans are assumed as sphere with constant volume
4. Coffee beans are homogeneous and isotropic
5. Moisture loss was diffusively regulated
6. The driving rate for mass transfer is proportional to X (moisture content).
7. Exothermic heat generation as well as water production is neglected.

The rate of temperature rise of the beans is due to two main contributes: the heat transferred from the gas to the beans by convection Q_{gb} and the heat produced due to vaporization of water inside the beans Q_{eva}.

The energy balance on coffee beans results in equation 5.7

$$m_{bd}C_b(1+X)\,\frac{dT_b}{dt} = Q_{gb} + Q_{eva} \tag{5.7}$$

where m_{bd} is the mass of dry beans in the chamber, X is the dry-basis moisture content and the specific heat capacity of the bean, according to Alonso Torres et al. [1] is calculated by

$$C_b(1+X) = 1{,}009 + 0{,}007T_b\,[°C] + 5X \tag{5.8}$$

The rate of heat transfer rate between gas and beans is defined as

$$Q_{gb} = \mathrm{G}C_a\left(T_{gi} - T_{go}\right) \tag{5.9}$$

G is the air mass flow rate, C_{pa} is the specific heat capacity of the air and the difference in air temperature is given by

$$T_{gi} - T_{go} = (T_{gi} - T_b)(1 - e^{-\left(\frac{h_{eff} A_{gb}}{G C_a}\right)}) \quad (5.10)$$

The global heat transfer coefficient between air and the coffee bean, as proposed by Alonso Torres et al. [1] is

$$h_{eff} = \frac{he}{1+0,3*Bi} \quad (5.11)$$

where the number of Biot (Bi) is defined as $Bi = {h_e d_b}/{k_b}$ with k_b is the bean thermal conductivity estimated by Cardoso et al., [14].
The heat transfer coefficient was calculated by rearranging the Ranz-Marshall equation (5.12).

$$h_e = \frac{k_a}{d_b} * \left[2 + 0,6 * \left(\frac{\rho_a V_a d_b}{\mu_a}\right)^{0,5} * \left(\frac{C_a \mu_a}{k_a}\right)^{\frac{1}{3}}\right] \quad (5.12)$$

The gas to beans heat transfer area, A_{gb}, depends on the dimensions of the beans, assumed being a sphere with constant diameter. The total surface area of the beans is assumed to be

$$A_b = \left(\frac{m_b}{M_b}\right) \pi d_b \quad (5.13)$$

where M_b is the weight of a single bean, m_b is the total weight of the beans loaded in the chamber and d_b is the bean diameter.
At each time instant a portion of the beans is in contact with the metal on the bottom of the drum, while the remaining part is in contact with the gas, pushed by the rotatory movement of the drum. So, as suggested by Di Palma et al. [23] an adjustment factor P_{bm} representing the percentage of contact area of a single bean to the metal should also be considered. The contact area between gas and beans will be $A_{gb} = A_b(1 - P_{bm})$.
In this work, where only the heat transfer from air to bean is considered, the P_{bm} factor will be neglected and as a simplification it will be used $A_{gb} \cong A_b$.
The second contribution of equation 3.7, Q_{eva} represent the heat loss due to evaporation of water inside the bean and it is expressed as function of the latent heat of vaporization ΔH_{eva} and the rate of moisture change per unit dry mass of beans $\frac{dX}{dt}$.

$$Q_{eva} = m_{bd} \Delta H_{eva} \frac{dX}{dt} \tag{5.14}$$

The development of water evaporation model during the roasting process started from the mass equation of the flow rate of water out of the bean:

$$\frac{dm_w}{dt} = m_{bd} \frac{dX}{dt} = -A_b * N_w \tag{5.15}$$

where Ab is the surface of coffee beans and N_w is the water flux from the bean to the interface with air since the mass transfer is regulated by diffusion within the bean, and it can be expressed as

$$N_w = \rho_b k_w^{liq} (X - X^*) \tag{5.16}$$

where X is the mass fraction of water inside the beans and X^* is the mass fraction of water at the interface equal to $RH * {}^{MW_w}/_{MW_b}$.

RH is the relative humidity of the air assumed equal to 0,1 because when air is heated above 200°C it becomes very dry (HR<0.1 from Hernandez et al. [35]), PM_w the molecular weight of water and MW_b the molecular weight of coffee.

For the case analyzed, assuming the coffee beans as a sphere the mass transfer coefficient k_w^{liq} is defined equal to ${}^{15\, D_{eff\, w}}/_{d_b}$ [51]. (5.17)

The effective diffusivity is obtained considering that coffee bean is a porous media with inside discontinuity that represent obstacles to the moisture transport. These two resistances are expressed through a porosity factor (ε=0,5) and a tortuosity factor (τ=2). The effective diffusivity result as $D_{eff\, w} = \frac{\varepsilon}{\tau} * D_w^{liq}$ with D_w^{liq} that is water diffusivity, uniform in space and constant during processing time.

Including equation 5.16 in 5.17 in the flow rate of water, the moisture profile obtained is

$$\frac{dX}{dt} = -\frac{A_{gb} \rho_b k_w^{liq} (X - RH * {}^{MW_w}/_{MW_b})}{m_{bd}} \tag{5.18}$$

5.2.1. Model simulation

Starting from the previous consideration the system of equations developed is:

$$\begin{cases} \dfrac{dT_b}{dt} = \dfrac{GC_a(T_{gi} - T_{go}) + m_{bd}\Delta H_{eva}\dfrac{dX}{dt}}{m_{bd}C_b(1+X)} \\ \dfrac{dX}{dt} = -\dfrac{A_{gb}\rho_b k_w^{liq}\left(X - RH * {}^{MW_w}/_{MW_b}\right)}{m_{bd}} \\ C_{pb}(1+X) = 1{,}009 + 0{,}007T_b\,[°C] + 5X \\ T_{gi} - T_{go} = (T_{gi} - T_b)\left(1 - e^{-\left(\frac{h_{eff}A_{gb}}{GC_a}\right)}\right) \end{cases} \tag{5.19}$$

For the simulation of the equations proposed an Eulero forward approach with 10 seconds Δt step on Excel was used.
Since measurements on an existing plants was not possible, the values of G, V_g and m_{bs} used to validate the model are those proposed by Ntsitlola F. Bopape et al. [10] and all the constant used for model simulation are listed in the following Table 5.1.

Table 5.1: Constant parameters used for model simulation (Arabica coffee).

Parameter	Value	Unit
G	0,047	kg / s
C_a	1006	J / kg*K
v_a	0,7	m/s
ρ_a	1,276	kg/m^3
μ_a	$1{,}722*10^{-5}$	Pa*s
k_a	0,02435	W/m K
m_{bd}	4	$kg_{drymatter}$
d_b	0,0066	M
ρ_b	921	kg/m^3
T_{b0}	20	°C
X_0	0,105	$kg_w/kg_{dry\ matter}$
ΔH_{eva}	2790	KJ/kg
D^{liq}_w	$3{,}9*10^{-9}$	m^2/s
PM_w	18	g/mol
PM_b	194,2	g/mol

The model was solved at three different inlet air temperature set at 230°C, 250°C and 300°C. The resulted bean temperature profile and moisture profile as function of time are represented in the Figure 5.5.

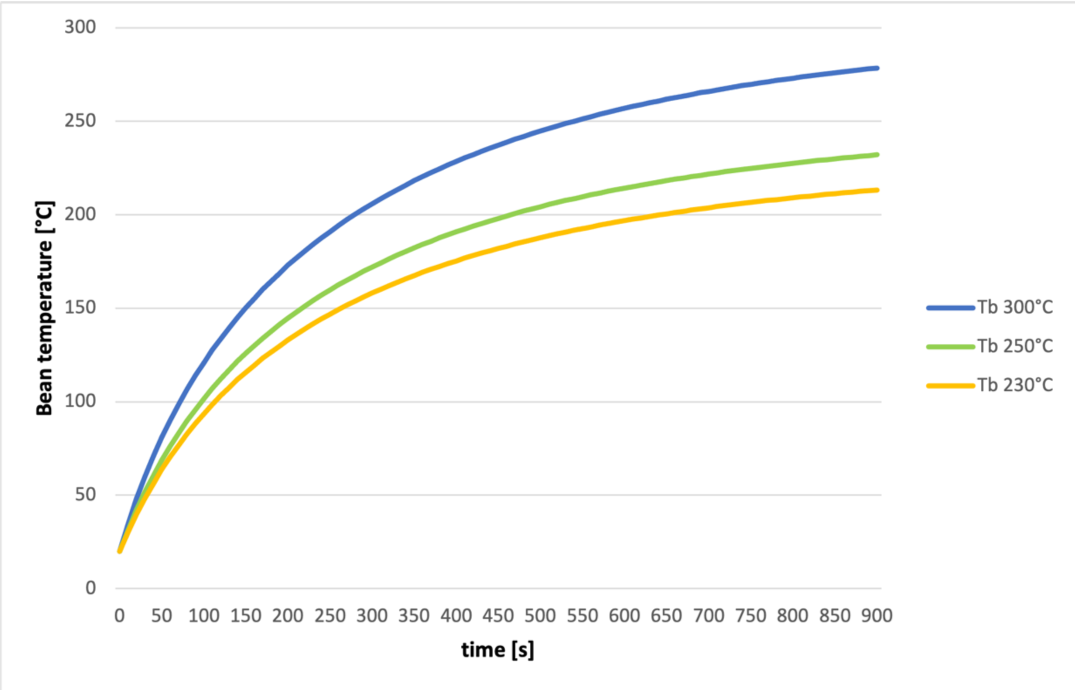


Figure 5.5: Evolution of bean's temperature versus time for different air temperatures. In the figure are highlighted the points where the grain reaches the optimum maximum temperature of 240 ºC. In the case of Tair =230° C it is not possible to reach this value.

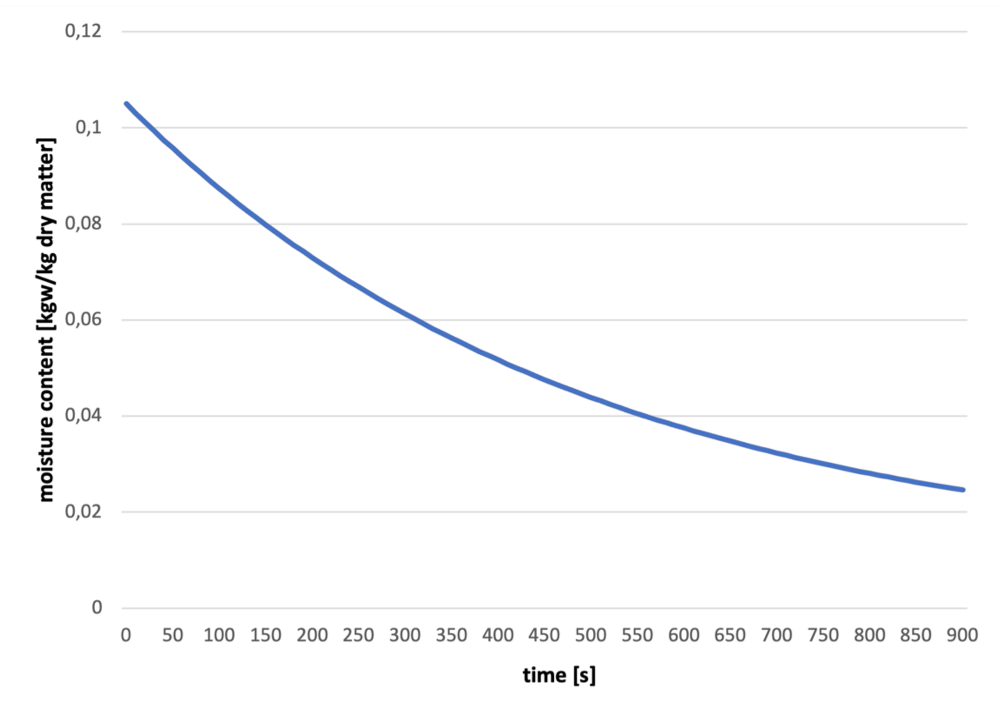


Figure 5.6: Evolution of bean's moisture content versus time.

The suggested model can be used in a satisfactory way to describe the behavior of the coffee bean's temperature versus time, in an hot air roaster.

The temperature profile (Figure 5.5) is in good agreement with the model proposed in literature although the heat generated by exothermic reaction is not included. This can impact on the beginning of the kinetics resulting in a slower increase of beans' temperature with respect to models based on Schwartzberg's equations.

The model proposed is based on a general convective heat transfer between hot air and beans and it doesn't include parameters specific of the roaster, hence, it could be applied to different roasting technologies to evaluate the general behavior of the bean temperature and the effect of the variables process parameters.

The moisture content simulation using equation 5.17 gives acceptable result (Figure 3.6) even if the pattern is not exponential as the one proposed in literature. In fact in the mass transfer analysis approach used in this work, the rate of moisture loss is function of X and time while in literature it is described by a semi empirical relation between X and T_b based on an Arrhenius – type equation.

A further validation of the proposed model can be done by comparing the temperature trend of the roaster T_r with that reported by Ntsitlola F. Bopape et al. [10]. The T_r profile is given by

$$\frac{dT_r}{dt} = K_t(T_b - T_a) \qquad 5.20$$

K_t is the thermocouple coefficient calculated as $K_t = {h_tA_t}/{m_tC_t}$.
The comparison is shown in Figure 5.7

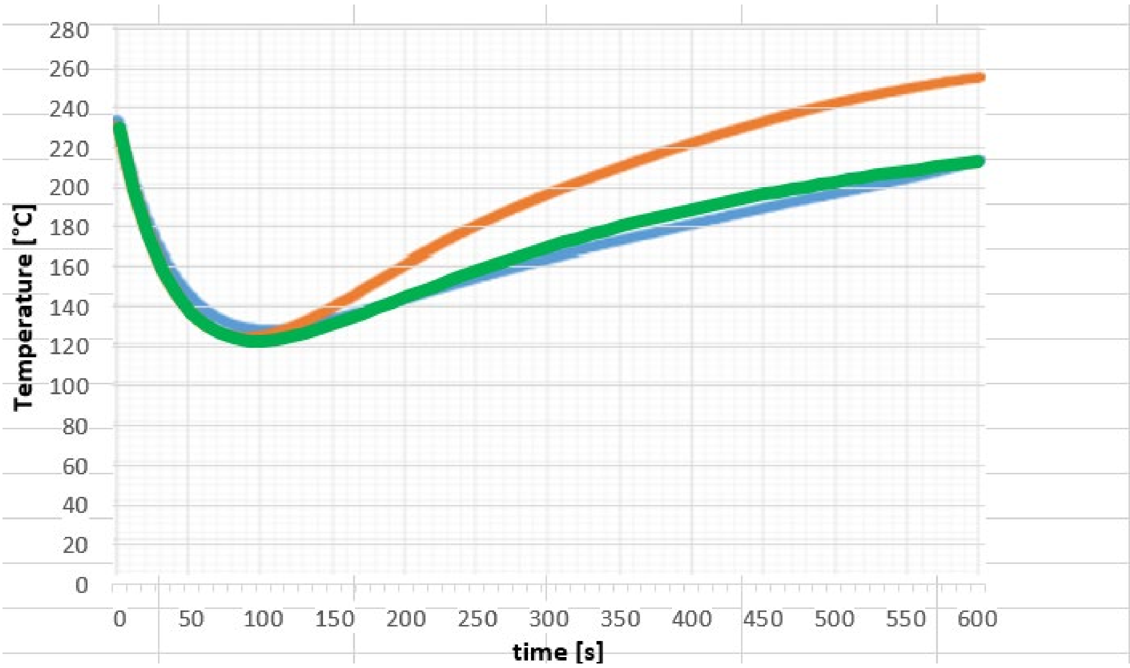


Figure 5.7: Comparison between model T_r and referencing T_r. Red line: referencing T_r, blue line: experimental T_r, green line: model T_r.

The model roaster temperature profile (green line) seems to fit the experimental data better, confirming the bondness of the results obtained.

6 Traditional roasting process with solar energy

The first alternative for roasting coffee proposed retains the same characteristics of the traditional process (a flow of hot air that passes over the coffee beans) but with a more sustainable approach. The idea behind the model is to heat air through a tube using linear parabolic concentrator (Figure 2.14). In this way it is possible to replace and save on the fuel to be used (avoiding CO_2 emissions), simulating in all and throughout the traditional process.

6.1. Model definition

To evaluate the feasibility of this system it is necessary to start from the sizing of the tube in which the air circulates. If the diameter is fixed by the manufacturer and by thermal requirements (keep the losses low), the length instead depends on the air temperature one wants to obtain. In the industrial roasting processes, it has seen that the air temperature entering the roster varies greatly from case to case, from 250°C (Hernandez et al., [34]) to 500°C (Schwartzberg, [70]). Consequently, it is easy to deduce that, as the desired T_{air} increases, the length of the pipe will increase, making the plant difficult to build.

The length of the pipe is obtained from an energy balance on the air that need to be heated up. For assumptions, the irradiation and convective Q_{loss} are neglected assuming that the receiver is well insulated (Consulente energia, [18,19]).

The equation to find the length Z of pipe is given by

$$\rho_a v A_p C_a \frac{dT_a}{dZ} = n_s \phi F \frac{dA_r}{dZ} \tag{6.1}$$

The density of the air in the tube is equal to $\rho_a = {}^{PPM_{air}}/_{RT}$ where P is the pressure, PM the molecular weight of air and R gas constant. The use of air at high pressure allows in fact to balance the pressure losses that lead to a reduction of air velocity. The parameter $n_s = \frac{Area\ subtended\ to\ the\ solar\ collector(A_c)}{Area\ subtended\ to\ the\ solar\ receiver(A_r)}$ is called solar concentration ratio or sun's number. In many cases the area subtended to the solar receiver is the projected area that, for a pipe, is approximated to $d_t \times Z$. The factor F is introduced to indicate the percentage of tube surface actually exposed to the sun's rays reflected by the parabola.

Φ is the solar power provided by the parabola is given by the equation (4.1) and it is assumed constant as the air specific heat C_a. The inlet area of pipe is defined as $A_p = {}^{\pi d_t^2}/_4$.

Integrating it obtains

$$\frac{PPM_{air}}{RT} v A_p C_a (T_{ao} - T_{ai}) = n_s \phi F d_t Z$$

$$Z(T,n) = \frac{\frac{PPM_{air}}{RT} v A_p C_a (T_{ao} - T_{ai})}{n_s \phi F d_t} \tag{6.2}$$

where T_{ai} and T_{ao} are the air inlet and outlet temperatures from the pipe.

6.2. Model simulation

To solve equation (6.2) the values used are reported in the following Tables 6.1 and 6.2.

Table 6.1: Numerical values used to size the pipe length.

Parameter	Value	Unit
ρ_a	2,73	Kg/m³
C_a	1006	J/kgK
A_p	0,00785	m²
v	10	m/s
P	3	atm
R	8,314	J/molK
PM_{air}	28,98	kg/kmol
T_{ai}	128,1	°C
T_{ao}	250 – 500	°C

F	0,5	
Φ	456	W/m²

The solar energy power Φ is given by equation (4.1). Its value is estimated referring to the average solar energy density in Italy collected by a Fresnel linear solar concentrator with the following specifics:

Table 6.2: Fresnel characteristics

Parameter	Value	Unit
L	5	m
w	1	m
n_{smax}	10	
A_c	5	m²
d_t	0,1	m
γ_r	0,9	
ϵ	0,9	
α_r	0,75	
Φ	456	W/m²

The length of the tube is a function of the outlet air temperature selected and the concentration ratio of the chosen device.

Table 6.3: The variation of Z as a function of T for n = 1 (a) and n = 10 (b). The value of Z shall be rounded up to the nearest whole.

Temperature (°C)	Z (m)
250	717
280	794
300	855
320	895
350	967
380	1042
400	1089
420	1137
450	1207
480	1276
500	1322

(a)

Temperature (°C)	Z (m)
250	72
280	80
300	85
320	90
350	97
380	105
400	109
420	114
450	121
480	128
500	133

(b)

To reduce the required length of the pipe, it is necessary to increase the power provided by increasing the parameter n_s, number of suns. For a Fresnel device, the maximum n_s is 10.

After heating the air, bringing it to the T of interest, it can be push into the roaster containing the coffee to be roasted. The process can be evaluated analogously to the traditional one. The phenomena of mass and energy transport are described by the system of equations (5.19). To solve it, the process parameters such as air mass flow rate G, heat transfer coefficient air-to-bean h_{eff} and coffee mass m_b must be determined, while the main physical properties of air and the constant values for coffee bean are reported in Table 5.1.
The massive air flow rate, passing through a single tube, is given by

$$G = \rho_a v A_p \tag{6.3}$$

According to data reported in Table 6.1. G is equal to 0,214 kg / s.
This value is strictly dependent on the area of passage of the pipe that is fixed while the velocity can be adjusted, although 10 m/s is already an high value.
Using the reference PI calculated in Chapter 5, equal to 4.7, the quantity roasted by G of 0,214 kg/s in 600s is

$$m_b = \frac{G \times t_R}{PI} = 27{,}2\ kg$$

The results from system (5.19) resolution provide the following temperature profile, with a trend like the one in Figure 5.5.

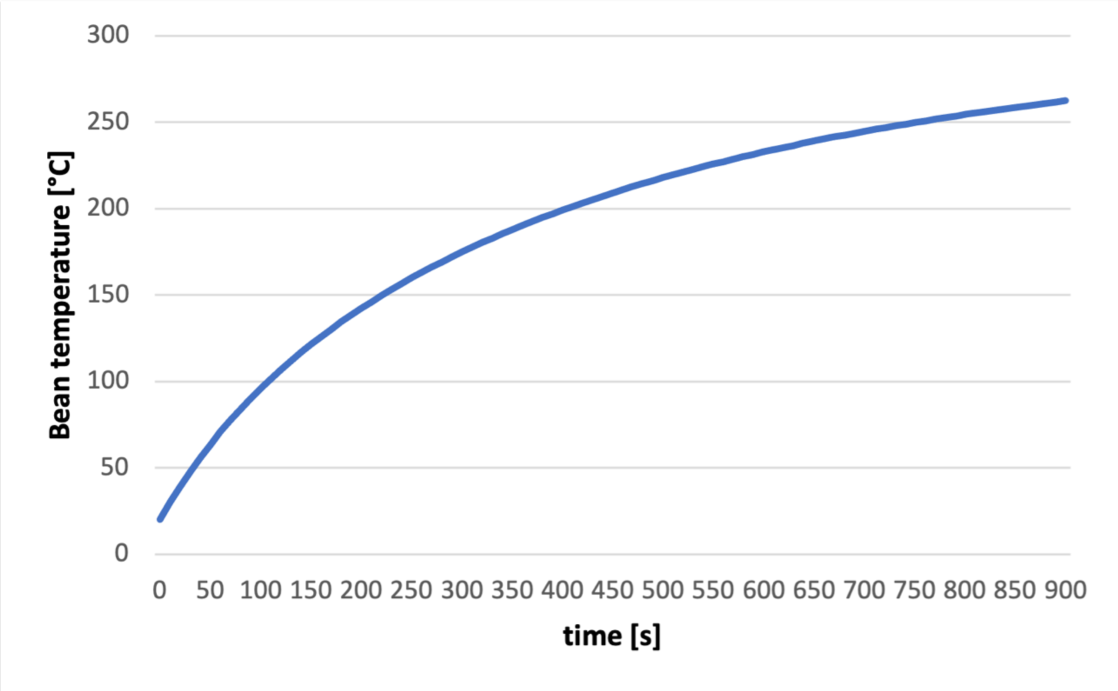


Figure 6.1: Bean's temperature profile for T_{air} in equal to 300°C

From the graph T_r, equal to 240°C, is reached around 660s although to estimate the mass m_b a reference time of 600s is used. This difference can easily be explained by the approximations present in the formula used to derive m_b, which does not take into account Q_{eva} and variable C_b, unlike the equation system (3.18).

6.3. System dimensioning

The feasibility of tubular solar concentrator system for coffee roasting is the main limitation of this process. In the previous paragraphs, the main process parameters such as Z, G and m_b, for air temperature of 300 °C and roasting time of 600 seconds, have been estimated and are resumed in Table 6.4

Table 6.4: Values of the main parameters used.

Parameters	Value	Unit
Z	85	m
T_a	300	°C
G	0,214	kg/s
T_{bi}	20	°C
m_b	27,23	kg

In the coffee process industry the production batches are greater than the value found, then it's necessary to perform a plant scale up.
It is possible to obtain the G_{tot} capacity necessary to process a certain quantity of coffee, fixed by the roaster capacity, in the time chosen by the producer. In industrial processes a large roaster can roast up to 400kg. If you want to produce the same quantity, in 600s, with the proposed model the required flow rate G_{tot} will be equal to

$$G_{tot} = \frac{PI \times m_b}{t_R} = 3{,}14\ kg/s$$

one orders of magnitude greater than the mass flow G passing through the single tube.
In order to satisfy quantity G_{tot} it is possible to adopt a configuration like the one shown in the Figure 6.2

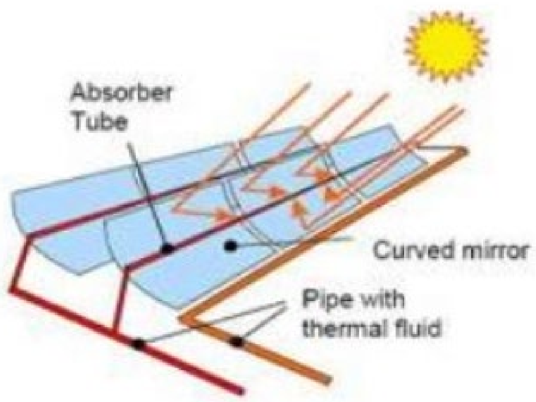


Figure 6.2: Parallel parabolic concentrators.

Concentrators are arranged in parallel rows, where each row rewinds the fixed flow G and finally merge individual flows into a single flow equal to G_{tot}.
The number of rows, and consequently of tubes to be used can be easily estimated as

$$n_{rows} = \frac{Total\ air\ mass\ flow\ required\ (G_{tot})}{air\ mass\ flow\ capacity\ of\ each\ pipe\ (G)} \tag{6.4}$$

and is equal to 14,7, which can be approximated to 15.
So to roast 400 kg is required a system of tubular solar concentrators arranged on 15 parallel rows 85 meters long tubes.
The corresponding parabolic surface can be calculated based on the specifications of the Fresnel device. The surface subtended to the collector of single device is equal to $A_c = L \times w = 5\ m^2$, where L is the length and w is the width. For a pipe of 85 meters, the number of parabolic trough per row to connect is

$$n_c = \frac{pipe\ length}{device\ length} = 17$$

The total surface can be calculated as

$$S_{collectors} = \text{n° of parabolic trough per row } \times \text{n°of row} \times \text{area of one parabolic trough} \qquad (6.5)$$

and it's equal to 1275 m^2.
The total space required for the actual installation must also take into account the distance that must necessarily be present between one row and the other. If this distance can be estimated at 0,5 m, the space actually required for such a plant is

$$\mathrm{A_{tot}} = \mathrm{S_{col}} + (\text{n° of rows} - 2) \times \text{lenght required (Z)} \times \text{ distance between rows} \qquad (6.6)$$

which results equal to 1827,5 m^2, 10 tennis field.

6.4. Model considerations

The proposed model provides more than reasonable results, according to the assumptions made.
In a real case, however, it is good to take into account some criticalities and aspects that have a significant impact on the real results.

6.4.1. Variables correlation

It has been shown that the various variables involved are closely related to each other and changing a reference value both the process and the sizing of the plant change accordingly.

To make the analysis easier, it is possible to identify three main variables, considering the others fixed by the manufacturer or by the dimensions of the device. T_{ao}, G_{tot} and the power provided by the linear solar concentrator can be considered as the main process variables.

T_{ao} is generally chosen by the manufacturer in the design according to the desired final characteristics of the product and the roasting times sought. In the proposed model the air can be brought to the chosen T_{ao} through the heating of the pipes, whose length depends on T_{ao} itself. During heating, the pipe lose heat with the ambient by convection and irradiation (Q_{loss}):

$$\rho_a v A_p C_a (T_{ao} - T_{ai}) = nF\Phi\pi d_t dZ - Q_{loss}$$

So, the values in the Table 6.3 are lower than the real one.

It must be remembered that solar energy, and consequently the power provided by parabolic trough, is not continuous during the day but varies considerably with cloud conditions. This weather unpredictability could lead the producer to choosing longer tubes to reach higher air temperatures or choosing to roast at longer times with lower T_{ao}.

The choice of high T_{ao} result also in a decrease in the PI of the system by equation (5.4). An increasing or decreasing of PI has an important effect on the plants scale up and dimensioning: fixed m_b and t_R lower is the PI lower will be the G_{tot} and vice versa. However, the real value of G_{tot} is always higher of the one calculated with the PI because the heat loss both from the pipe, as already mentioned, and roaster side are neglected in PI estimation.

Another consideration is the use of tubular solar concentrators. These devices are designed for high density fluids with low cryogenic points capable of transporting large amounts of heat for processes such as heating or evaporation of water. Air has considerably lower physical properties in terms of density and thermal diffusivity compare to the common working fluids. To increase the air density, the air can be compressed before being fed into the system by means of a compressor or a fan. Using an adiabatic compressor the air temperature at the outlet of the machinery, and then at the inlet of the tube, is greater than T_{ai} and can be estimated by the following relationship:

$$\frac{T_{ai}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

where $\gamma = {}^{C_v}/_{C_p}$.

So increasing P, G increases accordingly the equation (6.3) and the length of tube Z decrease because T_{ai} is higher than T_{amb}.

All these considerations about the main parameters and their influence on the others of interest can be resumed in the following Table 6.5:

Table 6.5: Correlations between parameters.

		PI	Z	Number of tubes	Number of device	Total Area
T_{ai}	↑		↓		↓	↓
T_{ai}	↓		↑		↑	↑
T_{ao}	↑	↓	↑		↑	↑
T_{ao}	↓	↑	↓		↓	↓
G_{tot}	↑			↑		↑
G_{tot}	↓			↓		↓
Φ	↑		↓		↓	↓
Φ	↓		↑		↑	↑

6.4.2. Sustainability

The main feature of this process is definitely its sustainability. The use of solar concentrators replaces that of fossil fuels, avoiding CO_2 emissions during roasting process. The amount of methane gas saved can be estimated by the proposed formula

$$m_{fuel}LHV = GC_g\left(T_{gi} - T_{amb}\right)$$

$$m_{fuel} = \frac{GC_g(T_{gi} - T_{amb}) \times t_R}{LHV} \qquad (6.7)$$

where methane LHV is 50 MJ/kg and T_{amb} is 25°C.
For a batch of 400kg roasted to T = 300°C in t_R of 600 seconds, with the corresponding G=G_{tot} capacity from Table (4.5), the mass saved is m_{fuel} = 9,9 kg.
The corresponding released CO_2 can be estimated from the chemical combustion reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

The molar ratio between CH_4 and CO_2 is 1:1.
The CH_4 moles are $mol_{CH_4} = {}^{9,9\ kg}\!\big/_{MW_{CH_4}} = 0{,}617\ kmol,$ so the equivalent kg of CO_2 released will be $kg_{CO_2} = 0{,}617 \times MW_{CO_2} = 27{,}16$ kg_{eq}.

This value is indicative and will be lower that the real one.

7 Roasting process with direct solar energy

The second alternative model proposed is based on the direct solar irradiation on coffee beans. Unlike the traditional process, in this case the beans are not heated by hot air but by the sun rays concentrated by the device. This means that the air surrounding the beans is at a lower temperature than the beans itself. The phenomena of energy and mass transport are therefore different from those of the traditional process. The analysis is focused on the roasting process from a macroscopic point of view but it could be expanded to assess the changes within the grain that occur at the microscopic level in relation to the absorption of photons. It is consistent to assume that roasting in this way takes place in a more homogeneous way being the photons absorbed in different quantities according to the colour change of the beans. At the same time, since the heat transfer conditions outside the beans are different, it is right to expect a different taste and aroma development.

The following models have been used to evaluate the feasibility of the process both in terms of beans' temperature and moisture content reached in an optimal roasting time and number of solar concentrator devices needed to provide the enough energy to perform a complete roasting.

7.1. Model definition

The model proposed refers to a insulated rotating drum with a hole through which the focused solar rays from the solar concentrator are allowed to enter.

The solar energy flux conditions in which the study is carried out refer to Italy, with an average Φ value of 750 W/m^2 (Chapter 4).

In recent years, many innovative solar heat tapping devices were introduced, but they are rarely applied for industrial purposes. In the previous model, the linear solar concentrator was the best solution.
However, in this case, among the available solar concentrating technologies, the Scheffler fixed-focus concentrator is the best suitable option for generating heat energy in medium to the high-temperature range with a variety of reflector sizes ranging from 2 to 60 m^2. The versatility of the Scheffler reflector is the fixed focus at the targeted position by automatically tracking the sun, which provides a uniform temperature distribution on the focus point throughout the day. At the focus point, a temperature up to 700°C is achievable depending on the size of the Scheffler reflector (Majeed et al.,[49]).
The Scheffler chosen for this laboratory scale simulation has a total area of 8 m^2. According with Majeed et al. [49], due to the optical losses, the effective useable surface of Scheffler devices is 4,6 m^2, about the 60% of the total area available.
The general energy balance on the beans loaded mass m_b is:

$$m_b C_b \frac{dT_b}{dt} = Q_{in} - Q_{loss} + Q_{eva} + Q_{react} \tag{7.1}$$

The power entered the system (Q_{in}) is provided by the solar concentrator and it's expressed as $Q_{in} = n_c \Phi A_c$ where Φ is the solar energy radiation, A_c is the concentrator surface and n_c the number of concentrators.
The energy loss from the system is given by the contribution of heat loss by convection from the bean to air (Q_{ba}) and the heat loss by the roaster (Q_r):

$$Q_{loss} = Q_{ba} + Q_r$$

In practical application, the roaster is coated with an insulating material which function is to limits the losses with the outside (Majeed et al.,[49]). So, if the natural convection between air and beans is present, the value of Q_r is much lower than Q_{ba} and for sake of simplicity it will be overlooked.
Q_{eva} is the heat necessary for the evaporation of the water contained in the beans and it's expressed by equation (5.14).
The last term of equation (Q_{react}) refers to the heat generated by exothermic reaction. As seen in the Chapter 3, the Maillard and Strecker reactions that occur in the bean

start at a T_b of 180-190°C. Since the heat generated by these reactions is low, its influence on the temperature profile will be neglected.
Making explicit the considered terms of the equation (6.8) the balance obtained is:

$$m_{bd}C_b(1+X)\frac{dT_b}{dt} = n_c\Phi A_c - h_{ba}A_{ba}(T_b - T_a) + m_{bd}\Delta H_{eva}\frac{dX}{dt} \quad (7.2)$$

where m_{bd} is the mass of dry beans in the chamber, X is the dry-basis moisture content and the specific heat capacity of the bean is described by equation (5.8).
The energy balance (7.2) must be coupled to the material balance for the variation of moisture X in the beans:

$$\frac{dX}{dt} = -\frac{A_{ba}\rho_b k_w^{liq}\left(X - RH\frac{MW_w}{MW_b}\right)}{m_{bd}} \quad (7.3)$$

7.2. Model simulation

7.2.1. Open drum

In first approximation a semi closed rotating drum is considered. The hole of the drum is not closed but remains open, putting the inside of the drum in direct contact with the outside air. In this way, the air temperature surrounding the beans can be considered constant, thanks to recirculation, and equal to the ambient temperature. The energy balance (7.2) becomes

$$m_{bd}C_b(1+X)\frac{dT_b}{dt} = n_c\Phi A_c - h_{ba}A_{ba}(T_b - T_{amb}) + m_{bd}\Delta H_{eva}\frac{dX}{dt} \quad (7.4)$$

The heat transfer coefficient h_{ba} is estimated by natural convection accordingly to the Fabbri et al., [29] hypothesis. In fact the rotation velocity of the drum applied is very low, between 2-5 RPM (Majeed et al., [49]).
The Nusselt relationship used for natural convection aroud a sphere is given by Fabbri et al., [29]:

$$Nu = (Nu_L^6 + Nu_T^6)^{1/6} \quad (7.5)$$

where

$$Nu_L = 2 + 0{,}868\ K\ Ra^{1/4} \tag{7.6}$$

$$\text{with } K = \frac{0{,}671}{\left(1+\left(\frac{0{,}492}{Pr}\right)^{9/14}\right)^{4/9}}$$

$$Nu_T = 0{,}11\ Ra^{1/4} \tag{7.7}$$

The Rayleigh number (Ra) is defined as $Ra = Gr \times Pr$ where

$$Gr = \frac{\rho_a^2 d_b^3 g\beta(T_b - T_a)}{\mu_a^2} \tag{7.8}$$

$$Pr = \frac{\mu_a C_a}{k_a} \tag{7.9}$$

β is the thermal expansion coefficient equal to $^1/_{T_a}$.

So, the value of h_{ba}, function of the bean temperature T_b, can be written as

$$h_{ba} = \frac{k_a}{d_b}(Nu_L^6 + Nu_T^6)^{1/6} \tag{7.10}$$

Starting from the equation reported, the following system has been solved to obtain the temperature and moisture profile as well as the number of concentrators required.

$$\begin{cases} m_{bd}C_b(1+X)\dfrac{dT_b}{dt} = n_c\Phi A_c - h_{ba}A_{ba}(T_b - T_{amb}) + m_{bd}\Delta H_{eva}\dfrac{dX}{dt} \\ \dfrac{dX}{dt} = -\dfrac{A_{ba}\rho_b k_w^{liq}\left(X - RH\dfrac{MW_w}{MW_b}\right)}{m_{bd}} \\ C_b(1+X) = 1{,}009 + 0{,}007T_b\ [°C] + 5X \\ h_{ba} = \dfrac{k_a}{d_b}(Nu_L^6 - Nu_T^6)^{1/6} \end{cases} \tag{7.11}$$

The data used to solve the system are reported in the following Table 7.1.

Table 7.1: Values of the main parameters used.

Parameters	Value	Unit
m_b	4	kg
X	0,105	kg_{water}/kg
T_{bi}	20	°C
Φ	750	W/m^2
A_c	4,6	m^2
n_c	1	
A_{ba}	3,95	m^2
T_{amb}	20	°C
ΔH_{eva}	2790	kJ/kg
ρ_b	921	kg/m^3
k_w^{liq}	$2,2*10^{-6}$	m/s
RH	0,5	
MW_w	18	g/mol
MW_b	194,2	g/mol
k_a	0,02435	W/mK
d_b	0,0066	m

The reference mass m_{bd} is a good approximation for an experimental roaster (Ntsitlola F. Bopape et al., [10]), while the contact area bean to air is calculated as $A_{ba} = {}^{m_{bd}}/_{M_b} \times S_b$.

With only one solar panel the maximum temperature that can be reached is around 64 °C, not allowing the roasting of coffee (neither the first nor the second crack), but only a partial drying of it.

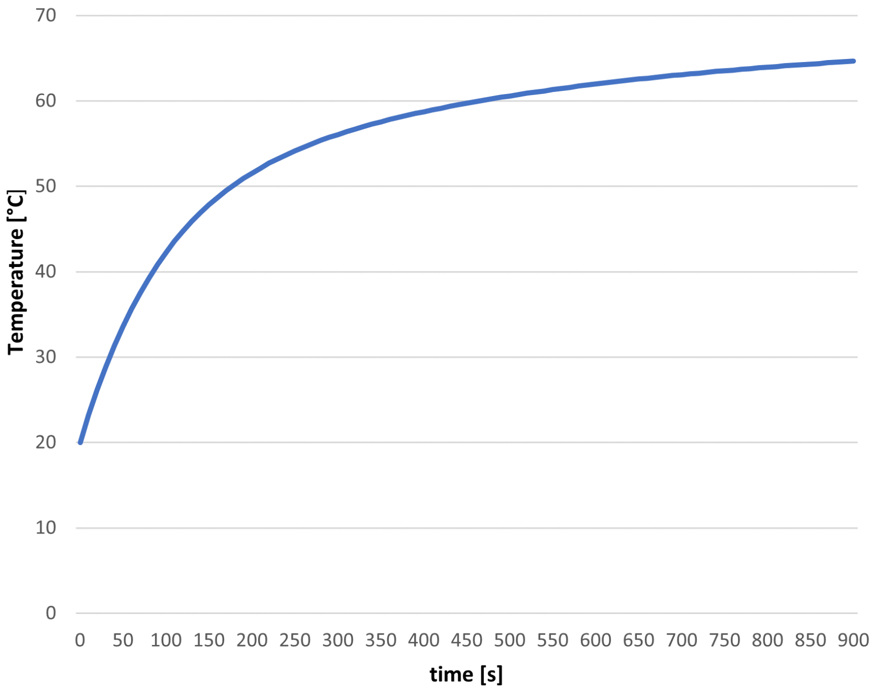


Figure 7.1: Beans temperature profile for n_c equal to 1.

As can also be seen from the Figure 7.1, to reach temperatures of 220-240 °C, necessary for a quality final product, it must be provided more power, so a greater number of panels n_c is required.

By placing 6 panels, for a total area of 48 m^2 and an effective usable area of 27.6 m^2, it is possible to reach the appropriate roasting temperatures

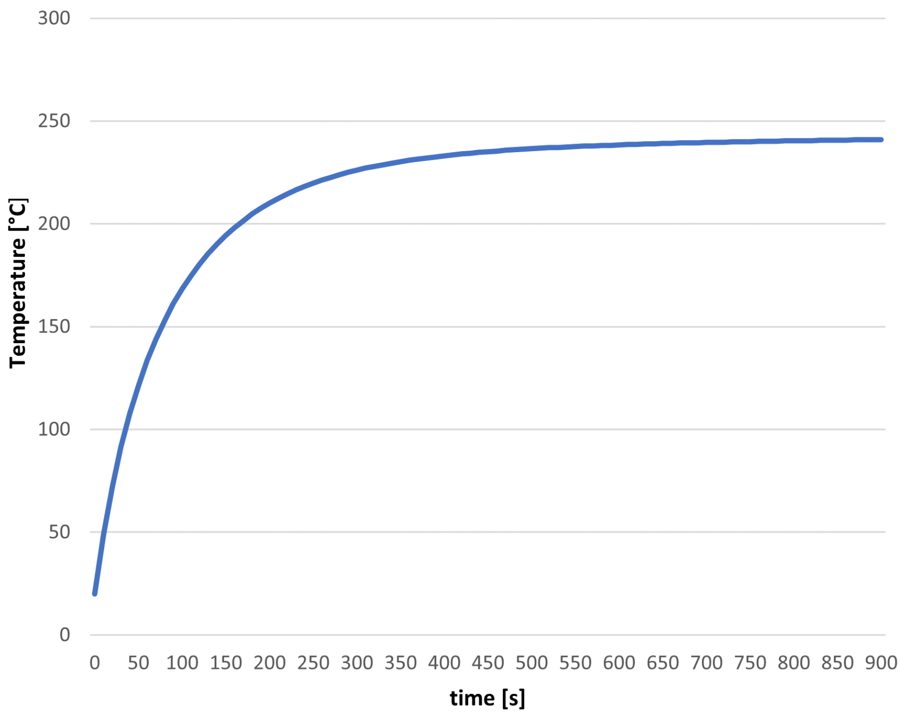


Figure 7.2: Beans temperature profile for n_c equal to 6.

The beans reach 240°c in 750 seconds. In the traditional case, analyzed in Chapter 5, this value of T_b is reached at t 470 seconds with a mass flow air G at T_g = 300°C. The moisture profile, instead, result more flat compared to the traditional case and the final moisture content obtained in the beans is 0,05929.

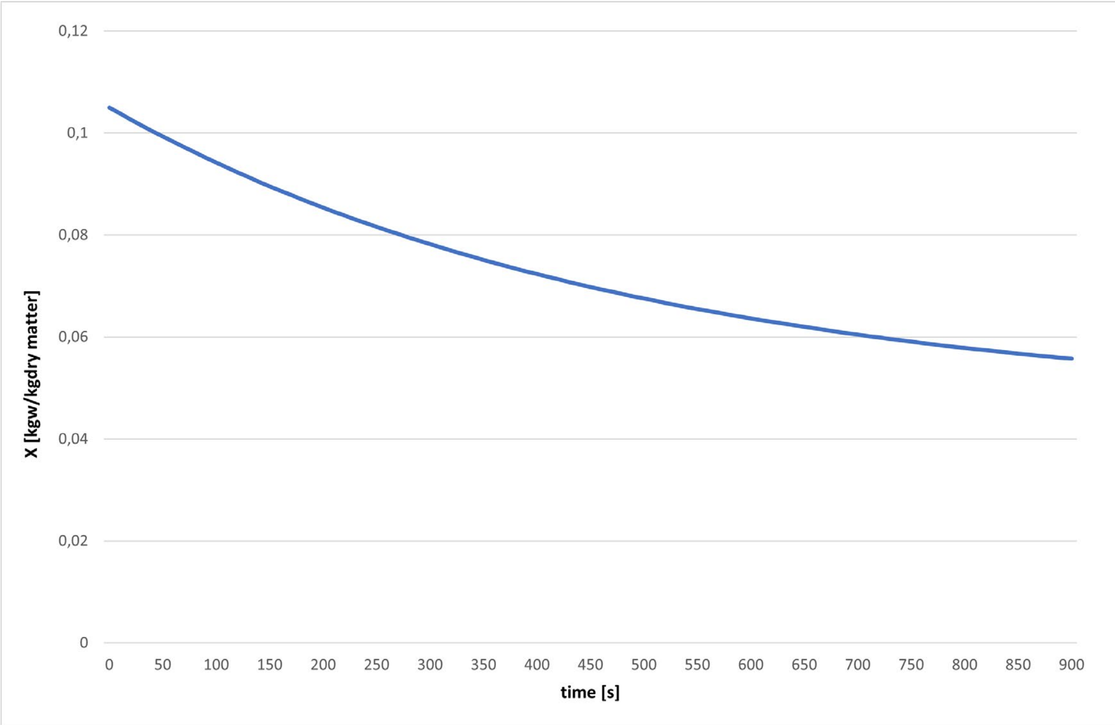


Figure 7.3: Bean moisture content

This is due to the fact that the minimum moisture value inside the bean is closely related to the relative humidity of the surrounding air in fact, in equation (7.3), $RH \frac{MW_w}{MW_b}$ represent the lower moisture limit attainable. Unlike the traditional case, there is no a dry air flow with RH ≅ 0,1 but the air relative humidity is determined by the environmental conditions.

As showed in Figure 7.4, decreasing the relative humidity of the surrounding air will also decrease the final moisture content of the beans.

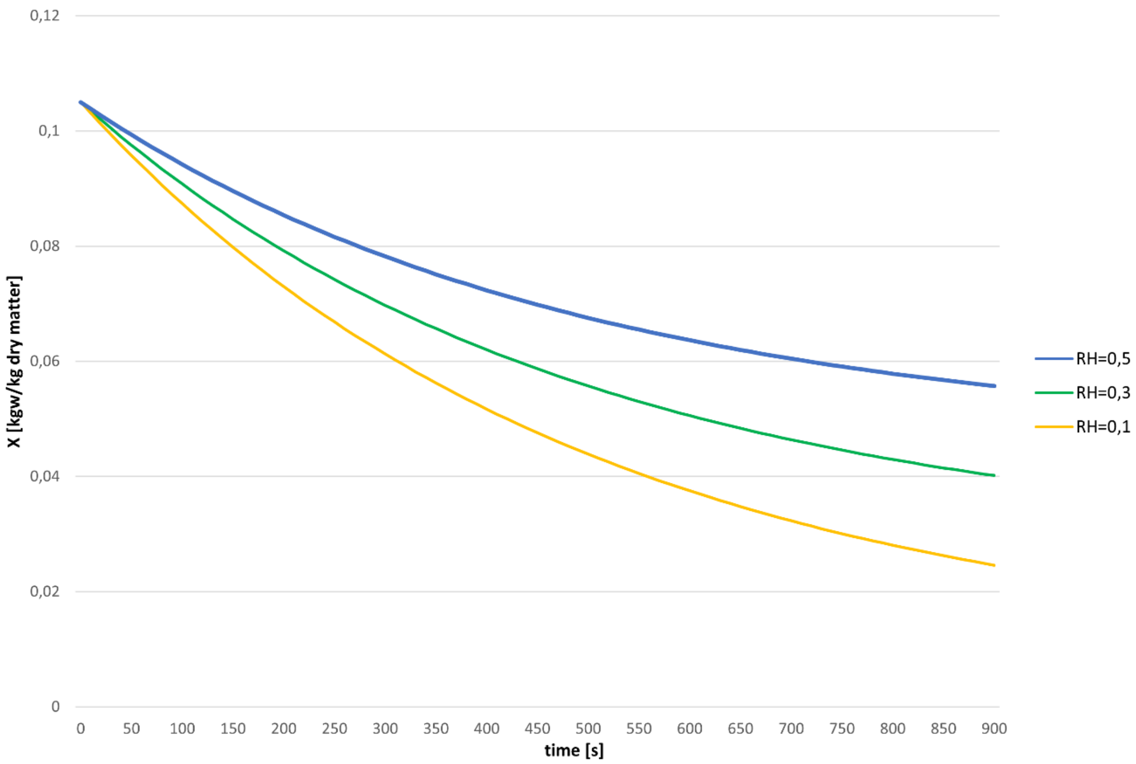


Figure 7.4: Moisture profile at different RH value.

7.2.2. Closed drum

In the most similar case to the real one, the roasting drum is closed by a highly transparent glass, thus isolating the system from the external environment. In this way it is no longer possible to consider the temperature of the air inside the roaster equal to the ambient temperature as in the previous paragraph.

For small experimental drums, such as the one under examination, the air temperature increases with that of the beans. One can therefore reasonably assume that the entire closed system is at T_b temperature, so $T_a \approx T_b$ and $T_r \approx T_b$ (Majeed et al., [49]).

Therefore in the energy balance on beans (7.2) the term of natural convection is negligible, while the Q_{loss} by the roaster must be accounted.

$$m_{bd}C_b(1+X)\frac{dT_b}{dt} = n_c\Phi A_c\gamma_r - Q_{loss} + m_{bd}\Delta H_{eva}\frac{dX}{dt} \tag{7.13}$$

where γ_r is the reflectivity of glass.

The can be estimated as $Q_{loss} = UA_d(T_b - T_{amb})$.

The new system to solve is

$$\begin{cases} m_{bd}C_b(1+X)\frac{dT_b}{dt} = n_c\Phi A_c - UA_d(T_b - T_{amb}) + m_{bd}\Delta H_{eva}\frac{dX}{dt} \\ \frac{dX}{dt} = -\frac{A_{ba}\rho_b k_w^{liq}\left(X - RH\frac{PM_w}{PM_b}\right)}{m_{bd}} \\ C_b(1+X) = 1{,}009 + 0{,}007T_b\,[°C] + 5X \end{cases} \tag{7.14}$$

The global heat transfer coefficient U is calculated as

$$U = \frac{1}{\left(\frac{s_{is}}{k_{is}} + \frac{1}{h_{ext}}\right)}$$

Where s_{is} and k_{is} are the thickness and the conductivity of insulator respectively. The conduction of the insulator and the heat transfer coefficient by convection with the external air (h_{ext}) were taken into account in the estimation of U.
The external coefficient can be derivate by the Churchill and Chu's Nusselt correlation for natural convection (Veynandt et al., [73]):

$$Nu = C \times Ra^n \qquad \text{with} \begin{cases} C = 0{,}48 \text{ and } n = \frac{1}{4} & for\ 10^4 < Ra < 10^7 \\ C = 0{,}125 \text{ and } n = \frac{1}{3} & for\ 10^7 < Ra < 10^{12} \end{cases}$$

The area of roaster A_d must be determined.
Industrial drums are studied on the basis of two parameters: the ratio of V_{gb}/V_d and the D/L ratio.
The V_{gb}/V_d is the ratio between green beans volume and roaster volume. It is in the range of 24%-32%. The D/L is the ratio between the drum diameter and the drum length. It's vary from 0,5-0,8 (Veynandt et al., [73]).
For roasting with direct solar energy, the roasters is arranged so that the aperture is perpendicular to the focal point of the panel. In many application the drum is tilted slightly (15°-20°) to allow the beans to concentrate near the hole where the sunlight is directed. With this configuration, the drum parameters are the standard ones. In this case the roaster is not considered inclined, so the ratio of the dimensions changes.
To make sure that all grains are directly exposed, the diameter of the drum must be large, greater than its length. These adjustments are used to increase the surface contact grains sunlight avoiding areas of possible shade (Veynandt et al., [73]).
This means that, as opposed to traditional machines, the D_t/L_t must be higher than 1, as can see from the Figure 7.5.

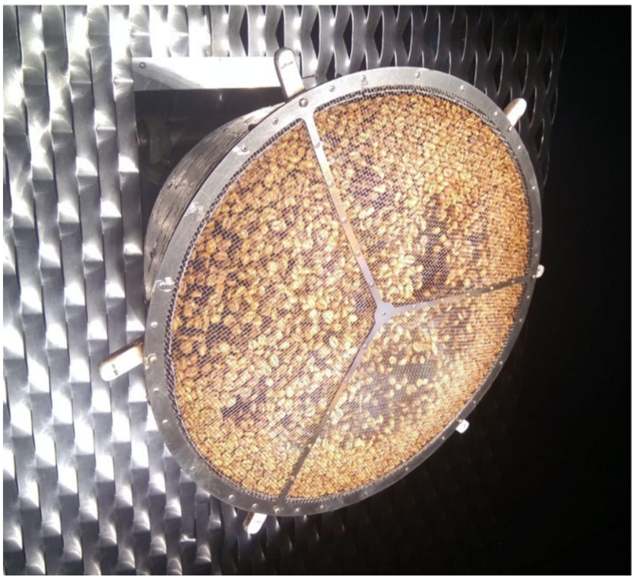


Figure 7.5: Solar coffee drum (from Purosole [66])

The approximate roaster volume V_r can be estimated by the equation proposed by Hidayat et al., [37]

$$V_d = V_{gb}(1 + volume\ expansion) \times F_s \times F_c$$

The volume expansion of beans after roasting is about 30%. F_s is the safety factor, necessary to ensure a minimum headspace of 55% (Hydayat et al.,[37]). It is equal to 2. Instead F_c is the corrective factor, related to the variety of beans dimension and the volume expansion. It is equal to 1,4.
The volume of green beans can be calculated as $V_{gb} = {}^{m_b}/_{\rho_b}$. The reference coffee mass and density is reported in Table 7.1.
The corresponding value of V_d is 0.016 m^3.
The dimensions of the roaster, based on the considerations made, are established for a D/L ratio of 1.25. All the data about the drum are reported in Table 7.2.

Table 7.2: Roaster dimensions.

Parameters	Value	Unit
D	0,33	m
L	0,2	m
V_r	0,016	m^3
s_{met}	0,005	m
s_{is}	0,01	m

D_{out}	0,345	m
A_d	0,217	m^2

After obtaining also A_r the system 7.14 can be fixed.
The bean temperature profile is the following:

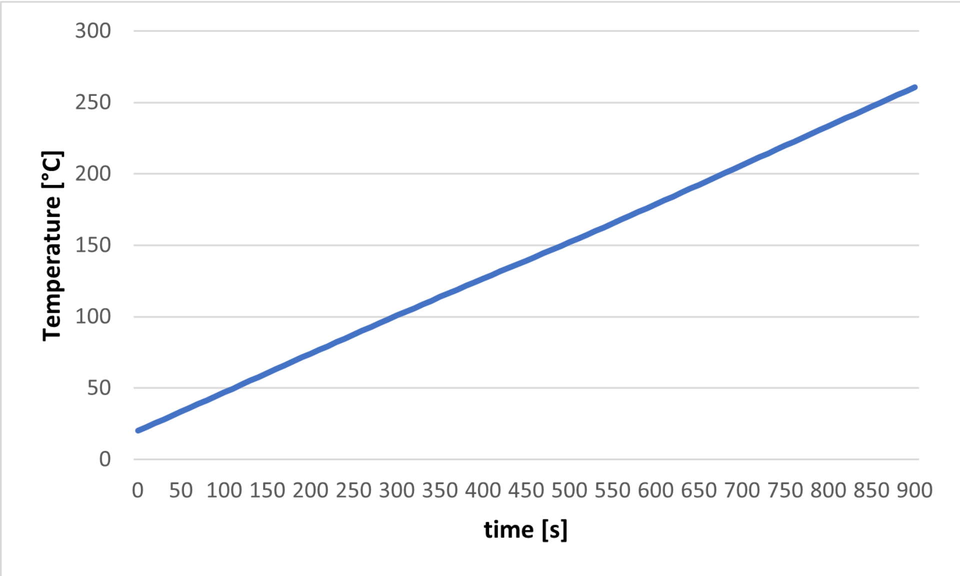
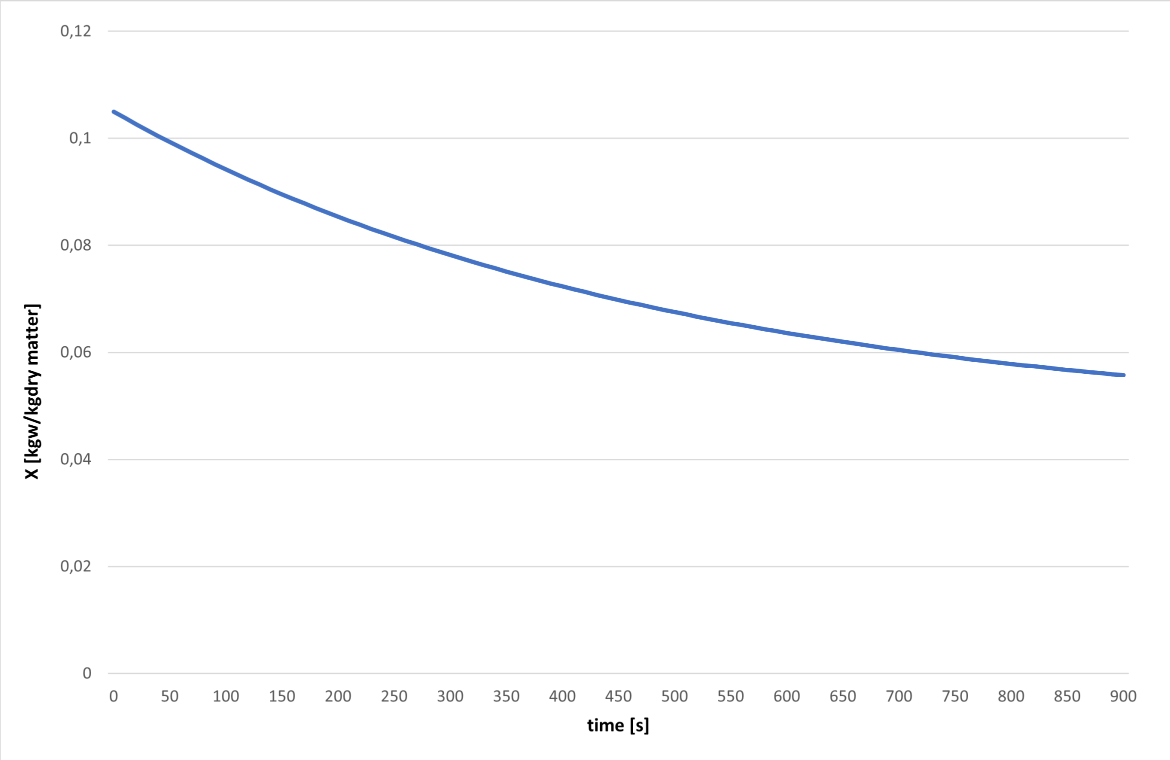


Figure 7.6: Bean temperature profile for closed drum.

The roasting time to reach T_b is 240°C is 850 seconds.
This profile differs greatly from the case of open drum. The temperature trend is linear. The stagnation temperature T_s, that is the temperature reached by the system when the term of heat accumulation is zero ($Q_{in} = Q_{loss}$), in this case is considerably high.
This is due to the losses of the roaster that are much smaller than those due to convection of the previous case, where indeed they were neglected.
Instead, the moisture profile of the beans is the same of the previous case



7.3. Model considerations

7.3.1. Open drum

The open drum configuration has some advantages and disadvantages. Keeping the hole open allows to disperse in the surrounding environment the moisture released by the grain but also the smokes and odors generated by the process itself. At the same time the heat losses due to convection are very high, bearing the system at a stagnation temperature of not more than 250 degrees. For this reason, a higher input power must be provided to complete the roasting and therefore a larger solar panel area is required.

As demonstrated, to roast an experimental quantity of 4 kg, an effective area of 27.6 m^2 is required, while for a batch of 80 kg are required 552 m^2. This value corresponds to a number of Scheffler panels equal to 69, a very high number for an industrial application.

The moisture content in this case strongly depends on the relative humidity of environment. This is the main issue for roasting with direct solar energy. It is impossible to reach moisture values in the grain equal to 1/2 % as in the traditional case where dry air is used.

7.3.2. Closed drum

Also closed drum configuration has some advantages and disadvantages.
Closing the hole with a glass cover means reducing the total power available for beans. In fact the glass reflects 10% of Q_{in}. On the other side, putting a cover reduce drastically the Q_{loss} from the beans and system.
For these reason the temperature of stagnation is significantly higher than the previous case. This means that the temperature control of the system, made by the thermocouple inside the drum , is a critical aspect.
Differently from the other case, the reference mass of 4 kg can be roasted with one panel, while to roast a batch of 80 kg an effective panel surface of 92 m^2 is required corresponding to 20 solar panel. Also for the closed drum, the final moisture content in the beans is an issues, but can be overcome by choosing to equip the drum with a purge. In a closed system in fact there is a risk of reaching the limit of air saturation that prevents further evaporation of water. When this relative humidity limit is reached, it is necessary to remove the air from the drum and inject new air to avoid counter-diffusion. In this way, fixing a dehumidified air mass flow, the moisture content inside the beans can be brought to the corrective values of 1/2 %.
In the following Figure 7.7 is reported the trend of moisture content in the beans in relation to the different relative humidity of the fresh air

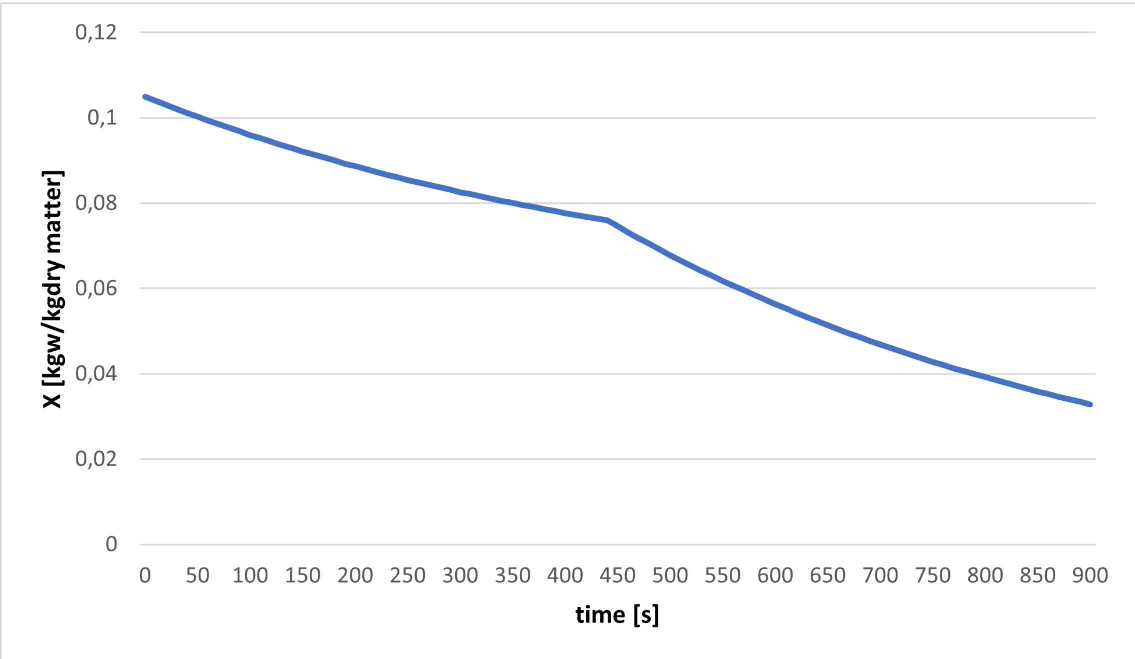


Figure 7.7: Moisture content with dehumidified air mass flow

The solution adopted to overcome the moisture problem has some important implications on the system.

Fresh air not only allows to reach the right moisture content but also allows to cool the drum and to keep under control the beans temperature by lowering the stagnation temperature of the roaster.

7.3.3. Sustainability

The sustainability approach of solar roasting can be quantified as made for the pipe case. The amount of methane gas saved can be estimated by the proposed formula

$$m_{fuel}LHV = GC_g\left(T_{gi} - T_{amb}\right)$$

$$m_{fuel} = \frac{GC_g(T_{gi}-T_{amb})\times t_R}{LHV}$$

where methane LHV is 50 MJ/kg and T_{amb} is 25°C.

In open drum, the reference mass of 4 kg is roasted in t_R of 750 seconds. The corresponding air mass flow G required to process this quantity can be estimated starting from the PI of traditional case (equation (5.4)). The G value obtained is equal to 0,025 kg/s.

From equation (6.7) can be calculated the amount of m_{fuel} saved. It is 0,11 kg.

The corresponding released CO_2 can be estimated from the chemical combustion reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

The molar ratio between CH_4 and CO_2 is 1:1.

The CH_4 moles are $mol_{CH_4} = {}^{0,11\ kg}\!/_{MW_{CH_4}} = 0,006\ kmol,$ so the equivalent kg of CO_2 released will be $kg_{CO_2} = 0,617 \times MW_{CO_2} = 0,2695$ kg_{eq}.

This value is indicative and will be lower that the real one.

Finally, also for both these cases is important to remember that the solar energy is not constant during the day , but change a lot in relation to the weather conditions.

8 Conclusion and future developments

The main objective of this study was to provide a different point of view to the coffee roasting process, meeting the increasing need for sustainable processes. For about a decade, several companies have developed the desire to put on the market a high quality product that respects the environment. But it's essential to understand its feasibility in practical and economic terms. For this reason our study is presented as a general overview of the feasibility of alternative systems for roasting from a mathematical point of view. The results obtained are encouraging but will certainly be expanded and contextualized with experimental data. Our analysis start from the renewable heat sources that can be used for roasting process. They are solar energy and biomass. While biomass only replaces fossil fuels without the need to study the case being the same as the traditional one, for solar energy it is necessary to deepen the roasting mechanism in order to define its feasibility and limits, and then the final product quality. Suffice it to say that the conditions under which the process takes place are already simply opposite. In the traditional case, coffee is processed in indoor large plants (up to 400 kg), while to use solar energy must work outdoors, under the environmental conditions with medium small plants (up to 80-120 kg). This makes, as already mentioned in previous chapters, the process itself much less controllable and manageable in terms of production, being the solar energy discontinues during the day. According to estimates of Purosole [66] in southern Italy, the daily production of coffee with solar energy does not exceed three hours equivalent to the industrial. This estimate is also valid with an excellent approximation for the two solutions proposed and evaluated: the use of linear parabolic concentrators with hot air circulating in the tube for a simulation of traditional process and the use of solar panels for a process with direct contact between sunlight and coffee beans. The analysis of these models refers to the study on the traditional process. A review of the literature on energy and matter transfer phenomena during the process was necessary to get a general picture. The results obtained for the traditional process approximate very well the T_b, X and T_r profiles of the beans reported by authors.

After framing the main dynamics related to traditional roasting, we moved on to evaluate the sustainable alternatives proposed. The first treated case, in which the air passes through the tubes of linear solar concentrators, showed that the obstacle is the dimensioning of the solar system. In fact, the roasting process itself is conducted in the same way as the current one, with hot air that gives heat to the coffee beans. The feasibility of the model thus, passes not from the evaluation of the temperature of the coffee or the roasting time but from the required surface of linear parabolic collectors and the number of tubes necessary for the reference air mass flow rate. From the obtained data it is well noticed that, due to the physical properties of the air, the area necessary is high and will correspond in practice to costs of Capex and Opex meanings. It can therefore be said that this solution makes it possible to obtain roasted coffee in a sustainable way, but it could be difficult to achieve. The second case is divided into two subcases. In both there is a roasting process very different from the traditional one. Sunlight is concentrated through reflectors inside a rotating drum directly on the coffee beans. depending on whether the drum hole is open or closed you have two similar models but with different assumptions and distant results. The feasibility of these two systems seems to be greater than the tube model. The roasting process is completed and the space requirement is less. Remember that the distances between the panel and the drum, the inclination of the drum and the alignment between the hole and the focal point are studied and optimized. Unlike linear parabolic concentrators, where the reflector and the tube are in a single system, in these subcases, the two devices are independent.

A further advantage, in addition to sustainability, of the latter case could be in the final value of the product itself. The roasting with direct contact takes place on several levels inside the bean and is not immediate and rapid. The photons are absorbed according to the wavelength that is to the different gradation of colour that varies within the beans . It’s fair to expect that the roasting with solar energy is more homogeneous and gradual. Another interesting aspect concerns the taste and aroma of the final coffee. In the traditional process the air flow not only gives heat to the grain but also takes away with it the volatile compounds released by the grain itself in a continuous way. In the case of natural roasting, however, the air surrounding the grain in quiet becomes saturated with these aromas, reaching a balance that prevents further diffusion of these substances.

For these reasons, a study of the aroma and taste of coffee produced with solar energy must be carefully conducted in order to demonstrate these hypotheses.

In conclusion solar roasting is feasible, requires major investments and a redesign of plant and production but you could get a natural product of higher quality than today, opening a new frontier of coffee experience.

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Variable	Description	SI unit
A	pre-esponential factor	1/s
A_{ba}	bean-air contact area	m^2
A_c	collector area	m^2
A_d	drum surface	m^2
A_{gb}	gas-bean contact area	m^2
A_p	passage área	m^2
A_r	receiver area	m^2
C_a	air specific heat	J/kgK
C_b	bean specific heat	J/kgK
c_b	bulk concentration	mol/m^3
C_{bd}	dry bean specific heat	J/kg_dK
C_g	gas specific heat	J/kgK
c_{sb}	water concentration on surface bean	mol/m^3
c_w	water bean concentration	mol/m^3
C_w	water heat capacity	J/kgK
D	drum diameter	m
D_{out}	outer drum diameter	m

d_b	bean diameter	m
D_{eff}	effective water diffusivity	m^2/s
d_t	tube diameter	m
D_w	water material diffusivity	m^2/s
D_{ws}	water material diffusivity on bean surface	m^2/s
g	gravity acceleration	m/s^2
G	gas mass flow rate	kg/s
Gr	Grashof number	
G_{tot}	total gas mass flow rate	kg/s
H_a	activation energy	kJ/mol
h_{ab}	air-bean heat transfer coefficient	W/m^2K
h_{ba}	bean-air heat transfer coefficient	W/m^2K
h_e	heat transfer coefficient	W/m^2K
H_e	amount of heat produced thus far per kilogram of dry coffee	kJ/kg_{dry}
h_{ext}	external heat transfer coefficient	W/m^2K
h_{eff}	effective heat transfer coefficient	W/m^2K
H_{et}	total reaction heat of dry coffee	kJ/kg_{dry}
h_{gb}	gas-bean heat transfer coefficient	W/m^2K
k_a	air conductivity	W/mK
k_b	bean conductivity	W/mK
k_{is}	insulator conductivity	W/mK

k_w	water-bean diffusion coefficient	m/s
k_w^{liq}	water mass transfer coefficient	m/s
K_t	thermocouple constant	
L	drum length	m
LHV	lower heating value	kJ/kg
M_b	single bean mass	kg
m_b	beans mass	kg
m_{bd}	dry beans mass	kg_{dry}
m_{fuel}	fuel mass	Kg
m_w	water mass	kg_w
n	directional vector	
n_{rows}	number of rows	
n_s	concentration ratio	
Nu	Nusselt number	
N_w	water mass flux	kg/m^2s
P	pressure	Pa
PI	process index	
PM_b	bean molecular weight	g/mol
PM_{CH4}	methane molecular weight	g/mol
PM_{CO2}	dioxide molecular weight	g/mol
PM_w	wáter molecular weight	g/mol
Pr	Prandtl number	

q	power	W/m^2
Q_{eva}	evaporation heat	W
Q_{gm}	heat from gas to metal	W
Q_{mb}	heat from metal to bean	W
Q_{react}	reaction heat	W
Ra	Rayleigh number	
Re	Reynolds number	
RH	relative humidity	
S_b	bean surface	m^2
S_{col}	total collectors surface	m^2
s_{is}	insulator thickness	m
s_{met}	metal thickness	M
T	variable temperature	K
t	time	s
T_a	air temperature	K
T_{ai}	inlet air temperature	K
T_{amb}	ambient temperature	K
T_{ao}	outlet air temperature	K
T_b	bean temperature	K
T_{bF}	final bean temperature	K
T_{b0}	initial bean temperature	K
T_g	gas temperature	K

T_{gi}	inlet gas temperature	K
T_{go}	outlet gas temperature	K
T_r	roaster temperature	K
t_R	roasting time	s
v	velocity	m/s
V_a	air volume	m^3
V_b	bean volume	m^3
V_d	drum volume	m^3
V_{gb}	green bean volume	m^3
w	bean humidity	kg_w/kg
X	bean moisture content	kg_w/kg
Z	tube length	M
β	thermal expansion coefficient	1/K
α_a	air thermal diffusivity	m^2/s
γ_g	glass reflectivity	
γ_r	receiver reflectivity	
δ	solar energy flux	W/m^2
ΔH_{eva}	latent heat of evaporation	kJ/kg
ε	porosity	
μ_a	air dynamic viscosity	Pas
ρ_a	air density	kg/m^3
ρ_b	bean density	kg/m^3

τ	tortuosity	
Φ	solar power per m^2	W/m^2