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Energy use of cork residues in the Portuguese cork industry

Ricardo Nepomuceno Pereira
Escola de Ciências e Tecnologia
Universidade de Évora, Évora, Portugal
e–mail: ricardop@uevora.pt

Isabel Malico*
Escola de Ciências e Tecnologia
Universidade de Évora, Évora, Portugal
LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
e–mail: imbm@uevora.pt

Paulo Mesquita
Escola de Ciências e Tecnologia
Universidade de Évora, Évora, Portugal
e–mail: paulomesquita00@gmail.com

Adélia M.O. Sousa
Escola de Ciências e Tecnologia
Universidade de Évora, Évora, Portugal
ICAAM, Évora, Portugal
e–mail: asousa@uevora.pt

Ana Cristina Gonçalves
Escola de Ciências e Tecnologia
Universidade de Évora, Évora, Portugal
ICAAM, Évora, Portugal
e–mail: acag@uevora.pt

ABSTRACT

Cork oak ecosystems play a very important environmental and socio-economic role in the Mediterranean basin. Their maintenance relies highly on the cork industry, which in turn, is dependent on these ecosystems. Despite the positive impacts of the cork industry, this is an energy-intensive sector, with a strong need for process heat. Therefore, a careful management of heat consumption is important to minimize its impacts. Being Portugal the world leader in the cork industry, this paper characterizes the Portuguese cork industry and gathers information on the production processes of cork products, with special focus on the generation of residues, heat consuming processes, heat production technologies and energy sources. The study relies on a compilation of data from several sources: statistic offices, industrial companies and associations and scientific literature. Cork powder is the main waste of the cork industry. It is already being valorised for heat generation in many industrial units, but it can further contribute to the reduction of the carbon footprint of this industrial sector.

KEYWORDS

Biomass; Cork; Industry; Residues; Cork Powder; Energy; Process Heat

*Corresponding author

INTRODUCTION

Portugal plays a very important role in the global cork sector, being the largest producer of natural cork in the world. The country is responsible for the production of about 100 thousand tonnes of cork products per year, which corresponds to a 50% world share [1]. The production and extraction of raw cork material, i.e, bark of the cork oak, are carried out in the forest. Among other environmental benefits underpinning the exploitation of the cork oak ecosystems for the production of raw natural cork, carbon sequestration is a direct contribution to the reduction of the greenhouse gas concentrations in the atmosphere. However, cork processing activities consume considerable amounts of process heat [2], which is produced by combustion systems fired by fossil and solid biomass fuels.

The Portuguese cork industry generates large quantities of cork powder, which are estimated to be 30 thousand tonnes per year [3]. This subproduct is often defined as having particle sizes not suitable for the manufacture of cork granulate, which are usually inferior to 0.5 mm [4].The potential for incorporating cork powder into cork products is reduced and up to now it has mostly been used as a combustible fuel for process heat generation [5, 6]. Other applications are already in use or under investigation; the following examples are indicative: as filling agents for cork stoppers of lower quality, as briquettes and as an agricultural subtract [7]; as biosorbent of different types of pollutants and as active carbon for several applications [8]; and as a filler in hydroxypropyl cellulose [9].

The utilization of cork powder as an energy source has a strong potential, since its properties are suitable for thermochemical conversion, it is a carbon neutral fuel, mature high performance technologies exist and fuel saving costs are achieved. Among the available biomass heat production systems, thermochemical conversion by direct combustion continues to represent the most important route, since the technology maturity is high, costs are lower compared to other conversion processes and energy performance is high [10, 11]. Among the existing solid biomass combustion technologies, suspended combustion, cyclone-type pyrolitic dust burners and fluidized bed combustion boilers are important routes for the conversion of cork powder residues into process heat in an efficiently and reliable manner. Biomass combustion boilers can operate with a conversion efficiency of 75 to 85%, and their capacity range is very wide (few kilowatts to several hundred of megawatts).

The Portuguese cork industry integrates all types of activities related to the processing of cork, which include the preparation of raw natural cork planks, and the manufacture of stoppers, granulates and agglomerates. Environmental impacts and energy costs are major factors to consider in the economic and sustainable development of the cork processing industries. Feasible investments in energy systems suitable for cork powder are strongly driven by those factors and also by industry specificities in terms of thermal energy demand and cork powder availability. This specificities are very dependent on the type of activity and on the degree of development of the factory. The production methods and type of systems used influence significantly the input flows of raw material and energy at a certain cork factory [12]. As a consequence, the inputs for economic feasibility analyses of investment projects on cork powder energy systems can be quite different. Presently, there is no aggregated information about the main inputs to carry out a reliable feasibility analysis on cork powder energy systems for the various sectors of activity of the cork industry.

The main objective of this work is to gather relevant information to perform economic feasibility analyses of investments in systems for cork powder utilization in heat production systems. First, the importance of the Portuguese industry is characterized in terms of its production, international trade, structure and size. Then, the production processes of the most relevant cork products are presented, highlighting the processes where heat is needed and cork residues produced. The cork processing operations with process heat needs are described, and energy sources and consumption are characterized. In the end, cork powder properties and conversion technologies relevant for thermochemical conversion are presented.

The information contained in this paper is important in the first stage of the assessment of the techno-economic feasibility and/or the cost-benefit of investing in projects of energy systems based on cork residues. It highlights the aspects related to project contextualization, objectives and identification, and the aspects related to the energy analysis concerning the assessment of energy demand and supply.

METHOD

In order to carry out the proposed analysis, the followings step were performed: *i*) characterization of the dimension of the Portuguese cork industry (cork production, international trade and the structure of the sector) based on information from sources of statistical data and reports from the Portuguese cork industry association; *ii*) description of the production processes of cork products, in particular heat consuming and cork residue generation processes based on scientific literature and technical reports obtained from industrial companies; *iii*) characterization of cork residues, in particular cork powder, based on scientific literature; *iv*) characterisation of the available combustion technologies for cork powder-based heat production, with the support of information from technology manufactures and suppliers, and technical and scientific studies.

PORTUGUESE CORK INDUSTRY OVERVIEW

Figure 1 shows the production of cork in the world and the international trade of cork products for the main countries involved (countries with volumes lower than 5000 t are not included). As can be seen from Figure 1, Portugal was the largest producer, exporter and importer of cork products. Only Spain has production and trade quantities that are comparable to Portugal. Other countries, such as Germany, USA, France and Italy, have a significant role in the import markets of cork products. The primary production of cork is concentrated in seven countries of the world, all in the Mediterranean basin, being the Iberian Peninsula responsible for four fifths of the world production: 49.6% in Portugal and 30.6% in Spain [1].

From Figure 1, it is clear that Portugal is an important global player in the cork industry, and, therefore, deserves a closer look. Table 1 shows the main indicators related to the Portuguese international trade in cork products. Statistics related to international trade in cork products use a harmonized classification denominated by the Combined Nomenclature (CN). Category 45 of CN concerns cork and articles of cork, and is subdivided in the following categories of products:

CN 4501 - Natural cork, raw or merely surface-worked or otherwise cleaned; cork waste; crushed, powdered or ground cork;

CN 4502 - Natural cork, debacked or roughly squared, or in square, rectangular blocks, plates, sheets or strip, including sharp-edged blanks for corks or stoppers;

CN 4503 - Articles of natural cork (except cork in square or rectangular blocks, plates, sheets or strips; sharp-edged blanks for corks or stoppers; footwear and parts thereof, insoles, whether or not removable; headgear and parts thereof; plugs and dividers for shotgun cartridges; toys, games and sports equipment and parts thereof);

CN 4504 - Agglomerated cork, with or without a binding substance, and articles of agglomerated cork (except: footwear and parts thereof, insoles, whether or not removable; headgear and parts thereof; plugs and dividers for shotgun cartridges; toys, games and sports equipment and parts thereof).

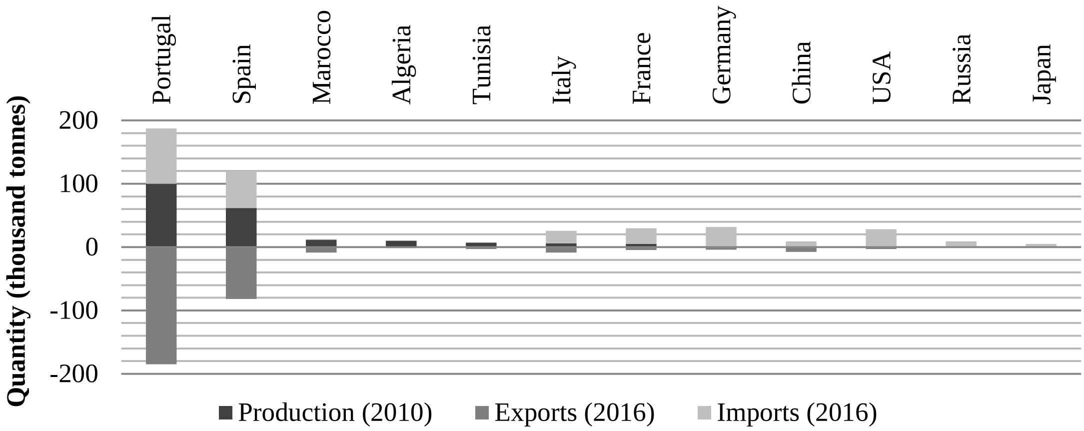

Figure 1. World production, Source: FAOSTAT 2010 cited in [1], and trade of cork and cork articles. Source: [13]

Portugal leads the export market for cork products in the categories CN 4503 and CN 4504. The export of products covered by categories CN 4501 and CN 4502 is led by Spain [13], but Portugal ranks second.

Table 1. Portuguese international trade of cork products by category in 2016. Source: [13]

2016		CN code				
		4501	4502	4503	4504	45 (total)
Imports	Quantity (kt)	81.9	2.0	1.8	1.8	87.5
	Value (million €)	123.9	10.4	31.9	8.4	174.6
	Share in value (%)	63.2	36.3	5.2	1.2	11.3
Exports	Quantity (kt)	44.0	0.5	15.0	125.4	184.8
	Value (million €)	49.0	2.4	425.1	459.8	936.3
	Share in value (%)	39.0	4.6	70.6	65.7	63.1

In relation to imports, Portugal presents the highest values for categories CN 4501 and CN 4502, being these results expected, since the products included in this category are the raw materials for the manufacture of the products included in categories CN 4503 and CN 4504. The share of the exports, expressed in value, of CN 4503 and CN 4504 clearly reflects the importance of the Portuguese cork industry in the processing activity.

Table 2 presents the key indicators of the size of the Portuguese cork industry for the main sectors of activity, namely the production or extraction of raw natural cork, and processing and wholesale trade in cork and cork articles.

Table 2. Key dimension indicators of the Portuguese cork industry in 2013. Source: [14]

Activity	Company actives by size	Number of companies	Average business volume (€)
Processing	Superior to 5 M€	38	18 560 345
	Between 495000 € and 5 M€	169	1 493 118
	Inferior to 495000 €	206	269 175
	Total companies	413	2 452 979
Wholesale trade	Superior to average (716 000 €)	24	1 971 743
	Inferior to average (716 000 €)	62	344 234
	Total companies	86	798 423
Extraction	Total companies	21	282 662

According to data presented in Table 2, 89% of the business volume of the Portuguese cork industry concerns the processing activity. The major fraction of the business volume is shared by the companies with actives superior to 5 million Euros and activity on the processing sector.

Table 3. Portuguese cork industry exports in 2015. Source: [1]

	Exports in value (Million €)	Exports in quantities (Thousand tonnes)
Stoppers (natural and agglomerate cork)	644.4	46.0
Building materials	228.0	123.0
Raw material	9.1	5.9
Others	17.7	2.5

Table 3 shows the exports made by Portuguese industry in relation to the demand market. The manufacture of stoppers for the wine industry is by far the activity in the Portuguese cork industry with the highest value of exports; in 2015 it represented 72% of the Portuguese export sales (44% concern natural cork stoppers and 28% agglomerated cork stoppers). The manufacture of agglomerated cork materials for construction (floor and wall coverings, insolation and others) represents 25% of the total export sales. Raw cork materials together with the manufacture of cork for other applications in decoration, transports, fashion, sports and other areas are responsible for the remaining 3% of the export sales.

INDUSTRIAL PROCESSES AND GENERATION OF CORK RESIDUES

This section describes briefly the production processes of the main cork products and identifies the operations with intensive process heat consumption and the types of cork residues that are generated in each process. Particular attention is given to cork powder residues, because its yield of production is considerably high in the majority of the cork processing units and its main use within the sector is as a source of energy for the production of heat. More detailed information on these aspects is presented in [2, 4, 12, 15, 16, 17, 18, 19].

Extraction of raw natural cork

Raw natural cork is obtained in the form of curved planks by the extraction of the oak tree bark, a specialized operation called "uncorking". After "uncorking", raw natural cork planks are subjected to a stabilization process, which consists of stacking them outdoors for at least six months. This operation may occur in the forest or in the facilities of the transformation industries.

Several types of cork residues and other solid biomass wastes can result from the extraction operations. They are: *i*) raw natural cork pieces resulting from the "uncorking" process and cork planks transport and/or handling; *ii*) cork parts, called wedges, formed at the base of the tree trunk in direct contact with the soil; *iii*) raw natural cork pieces considered to have lower quality, such as virgin cork, secondary cork and cork from pruning operations; *iv*) woody biomass from brunches and other solid biomass obtained in pruning operations, for example, leaves.

Preparation of natural cork planks

Figure 2a shows a diagram that represents the main steps involved in the process of preparing natural cork planks. The first step in the preparation of the planks is the boiling process where the material passes through a process of stabilization for a period of one to four weeks until they reach a moisture content of 8 to 16% [18] through a natural drying process. Depending on the boiling method, the stabilization period can be less than one week. After stabilization, the cork planks are subjected to selection and pre-processing operations, where the material not suitable for the production of stoppers is eliminated and the suitable material calibrated (edges are prepared and trimmed) and classified according to its use.

The cork residues generated such as the processed refuse from boiling and, cork shavings and defective planks from selection and pre-processing operations, although having different physical characteristics can be used for the production of granulated cork.

Manufacture of natural cork stoppers

Figure 2b shows a diagram that represents the main steps involved in the manufacturing of natural cork stoppers. The first stage includes the preparation of the stopper raw material (i.e., prepared natural cork planks) to obtain cork strips and squares, and the transformation of these pieces into semi-manufactured cylindrical stoppers. After this stage, the stoppers with defects are removed in a selection operation and the conforming material can be subjected to a drying process for moisture content reduction to 6±2% [18]. The second stage includes the dimensional rectification (rounding and chamfering) of the semi-manufactured stoppers, followed by a visual selection to classify them according to their appearance. At this stage, the stoppers are in the raw state and are subjected to a set of finishing operations before storage and/or packing, among which a drying process after washing to reduce the moisture content to the appropriate level. The manufacture of natural cork discs, bodies for bar-top stoppers and multi-piece stoppers is performed in a very similar manner to that of the natural cork stoppers. The processes can present different procedures and equipment, though. One example is related to the sanding of the sides of the discs. Another, for the case of multi-piece stoppers, is the insertion of an additional step after the preparation of the raw material (strips), which consists in the operation of gluing the cork pieces together. It should be noted that the prepared natural cork planks, before the beginning the first stage of the manufacturing process may optionally be subjected to a second boiling operation, which lasts at least thirty minutes, followed by a stabilization process to ensure that moisture reaches 8 to 16% [18].

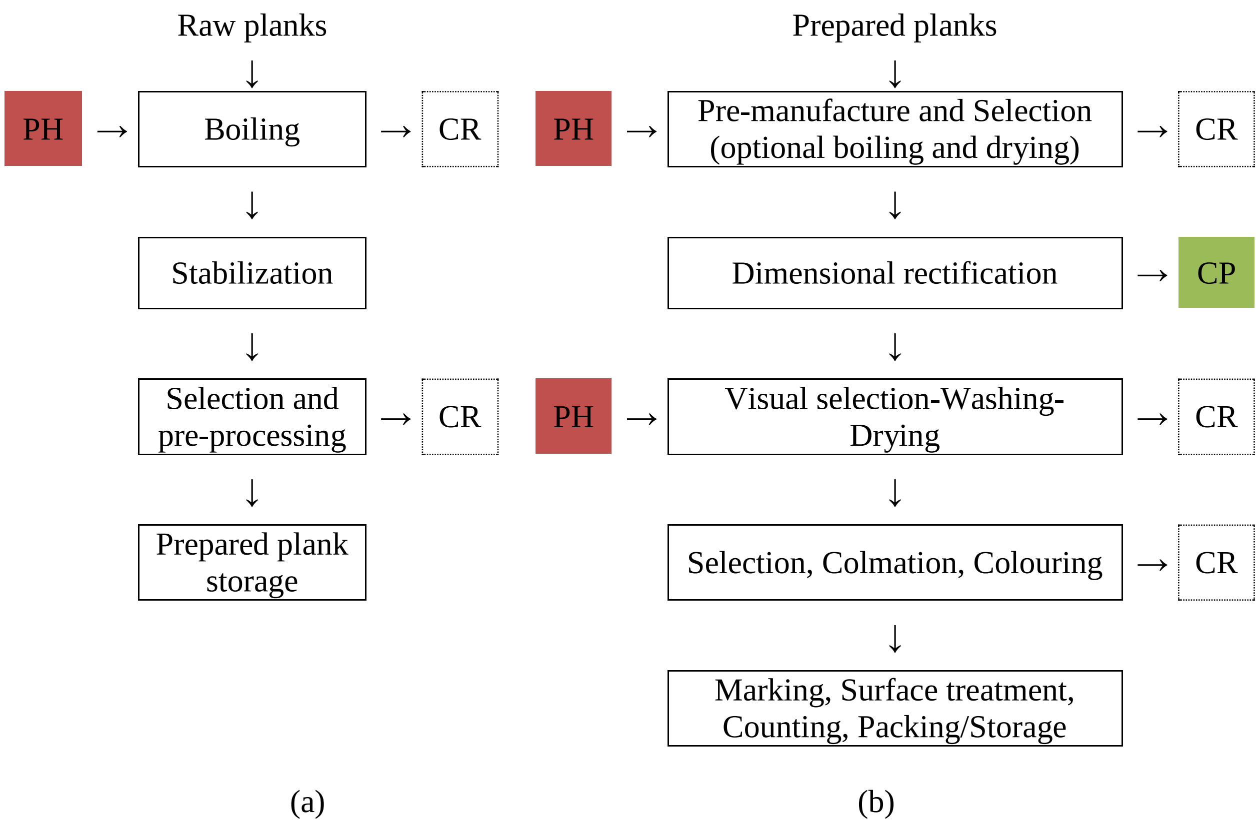

Figure 2. (a) Preparation of cork planks and (b) manufacture of natural cork stoppers. PH - process heat; CR - cork residues; CP - cork powder.

In the manufacturing of natural cork products, cork residues of various types are generated such as shavings, pieces and defective stoppers, usually used for the production of cork granulates. Cork powder residues are generated in operations of sanding and sawing the raw stopper carried out in the dimensional rectification process. Gil [4] estimates that about 25% of the raw material used in the production of natural cork stoppers is transformed into cork powder.

Manufacture of granulated cork

Cork granulates are produced from various cork byproducts that result from cork production and from the processing of cork. The granules may have different sizes and, the origin and quality characteristics of the material may condition its end use. Granulated cork is used for the manufacture of cork agglomerates, mainly wine stoppers, construction materials and decorative articles. The wine market requires high quality agglomerated cork and this is only achieved using granulated cork of superior quality obtained only from boiled cork waste, cork pieces derived from the preparation of cork planks or waste from the manufacture of natural cork stoppers.

Figure 3a shows a diagram that represents the main steps involved in the manufacturing of granulated cork. The production process begins with a magnetic and/or gravitational separation operation to remove unwanted materials (biomass, metals and stones). After this step, cork trituration (grinding) occurs, usually followed by a granulometric classification. Then, the small pieces of cork are granulated and graded again according to their granule size (for example between 0.25 and 8.0 mm for stoppers [18]) and to their bulk density. At this stage, cork granules are dried to ensure the adequate moisture content. Optional drying may occur before and after the trituration process and also before the densimetric separation process [17]. Finally, the material is stored to avoid the deterioration of its characteristics.

Most cork residues generated by the production of granulates are cork powders, which are not suitable for the manufacturing of agglomerates (usually with particle size less than 0.5 mm [7]). It should be noted that the production of linoleum (mixture of cork and many other compounds) utilizes the finer and denser granules [4]. Cork powder is defined as a material having a particle size of less than 0.25 mm and, within the cork industry, is mainly used as a combustible fuel or for filling agglomerate stoppers [7]. [4] indicates that in the production of granulates cork powder yield is about 22%. The cork powder is recovered through the use of suction systems and stored in silos (Saraiva 1998 cited in [4]). Another study [19] refers a yield for cork powder residue generation (<0.25 mm) of 35%.

Manufacture of agglomerated cork

Cork agglomerates are divided into two types: compound agglomerate (white agglomerate) and pure agglomerate (black agglomerate). The first is made of cork granules mixed with a binder and/or other additives, while the second is made up only of cork granules. The next paragraphs will separately describe, in general, the production process of these two products. White agglomerate is used to produce several cork products, but the main applications are for wall and floor coverings, and agglomerated cork stoppers. Black agglomerate is used for the manufacture of insulation materials mainly used in thermal, acoustic and vibration applications.

Figure 3b shows a diagram that represents the main steps involved in the manufacturing of agglomerated cork.

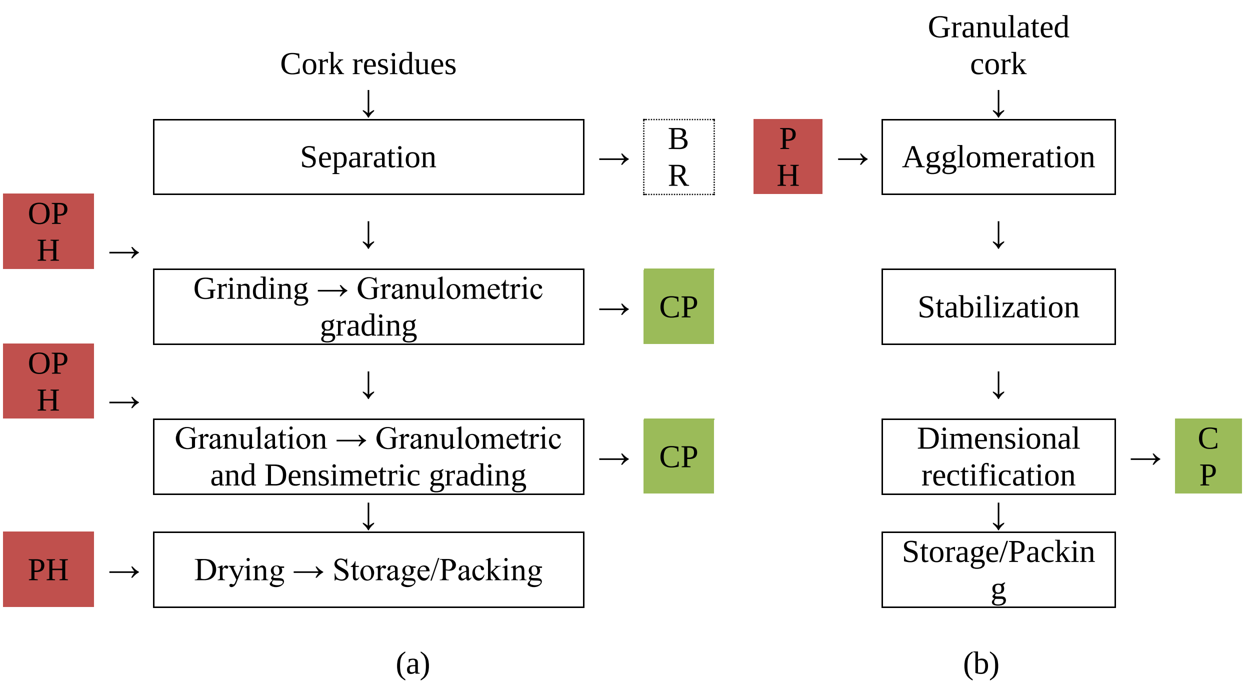

Figure 3. (a) Manufacture of granulated cork and (b) agglomerated cork. PH-process heat; CR-cork residues; CP-cork powder; OPH-optional process heat for drying.

The process of manufacturing white agglomerate begins by mixing the corks granulate usually with glue and an agglutinant. The mixture is inserted into moulds, pressed, and then the moulds are placed in a curing or cooking oven to initiate the agglomeration or agglutination process (where the glue added to the cork granulate is polymerized). After this stage, the material is removed from the mould and stabilized by cooling (in a natural or conditioned environment) to form a block of agglomerated cork. Then, the mechanical rectification of the block is performed to finish the product through cutting and sanding operations. Usually, in the case of materials with a higher density, dimensional finishing can also be done without cooling the blocks. The agglomerated cork blocks are usually of two types, rectangular and cylindrical, obtained with rectangular and cylindrical moulds, respectively. However, several other forms can be obtained, by post-processing the blocks, such as plates, sheets and tiles. White agglomerate products have different sizes, thicknesses, densities and finishing and are used for example in the manufacturing of floor and wall coverings, and technical and innovative applications.

The process of manufacturing agglomerated cork stoppers can be considered quite similar to the process described for the production of the composite cork blocks, although the agglomeration operation is done by extrusion or by tube moulding. In both methods (extrusion and tube molding), agglomerated cork "sticks" are obtained, which, after a stabilization period, suffer a correction in diameter and are cut according to the desired final product. Then, the final dimensional adjustments are made on the stoppers, which can include rounding and chamfering operations.

The process of making pure or black cork agglomerates is very similar to that of the composite agglomerate, as far as the sequence of operations is concerned. However, the agglomeration process is achieved by the injection of superheated steam through the mass of granulate, causing the cork resins to exude to the surface of the granules and the expansion of the volume of the granules [4].

The cork residues are generated during the dimensional rectification of agglomerated products, such as shavings from cutting operations and cork powder residues from sawing and sanding operations. The residues not suitable for the production of cork granulates are mainly used as a combustible fuel or as a filling agent in agglomerate stoppers manufacture.

THERMAL PROCESSES AND ENERGY CONSUMPTION

Heat consuming processes

As shown in the previous section, the heat-intensive processes in the cork industry are related to the boiling process of the natural cork planks, to the drying processes during the manufacture of natural cork products (planks, stoppers, disks, bodies and other pieces) and the production of granulated cork, and to the agglutination of cork granules during the manufacture of agglomerated cork products. Mandatory general practices for the manufacture of stoppers with premium quality grade require the adoption by the company of an energy saving plan and the reduction of its “footprint” to limit the environmental impact of the activity[18].

Boiling of natural cork planks. Boiling is performed through the immersion of the cork planks in a tank with clean hot water, at a temperature near 100 ºC and during a period of at least 60 minutes, which can be extended to 90 minutes [4, 18]. There are two methods for performing the boiling operation: traditional and continuous.

In the traditional method, the process water used for boiling is heated using a fixed bed furnace (fixed grill type) and the heat is delivered directly to the base of the tank (in contact with the combustion flame) in a direct fire system [4]. The tank is open, with masonry walls and a base usually made of copper [4]. The traditional system has two negative aspects [20]: *i*) water consumption is very high in order to achieve high efficiency in the extraction of unwanted compounds and, in order to restore the water losses by evaporation (significantly high in the traditional method) and by absorption of the cork planks; *ii*) the thermal process is inefficient due to the open tank system, which causes thermal losses to the ambient air and the consequent increase of the thermal load required.

Generally, in the continuous method, heat is produced in a combustion boiler and delivered to the tank in the form of steam that heats the boiling water. The boiler may be associated with a centralized heat production system or coupled directly to the tank [21]. In the continuous method, the tank operates closed and can be constructed entirely of stainless steel [21]. The systems operate with continuous filtration of the boiling water, automatic washing, and with energy recovery when the boiling water is replaced [21]. The tank can also carry out the preparation of the planks only with the introduction of steam. The control of the system for heating the process water can be fully automatic [21].

The consecutive use of the boiling water without suitable renovation causes an increase in the concentration of phenols and, consequently, the yield of extraction of undesirable compounds decreases considerably [20]. Moreover, contaminated planks may contaminate the rest of the planks, if the boiling water is not cleaned (from volatile compounds like TCA, which stands for 2,4,6-trichloroanisole, a substance extracted from the planks that contaminates the boiling water and, consequently, the incoming batch of unprepared planks). This is a common problem in the traditional boiling process [20]. Soares [20] presents a system operating in continuous mode that integrates, in its filtration system, a TCA removal equipment from which heat can be recovered. Another type of technology commercially available for sterilization and preparation of cork is based on the autoclave systems [21]. Mandatory practices require that the process water is regularly changed (single change or continuous renovation) and that the boilers are cleaned (solid and foam removal) and watered with clean water each time the process water is changed [18]. Standard quality cork products require two changes of water per week when in continuous use, and one change after a one-day break. Premium quality products require one water change per day regardless of the boiling process. This condition influences directly the consumption of heat.

Drying processes. The moisture content of raw cork and cork articles must be controlled and needs to present appropriate levels, since it affects the quality of the products and, obviously, influences the commercial value of the cork articles produced. The most common method for drying cork materials is through a conditioned environment with heated air. The contact between the surface of the material and the surrounding hot air causes the evaporation of the water contained in the material [22] and an evaporative cooling process is established in the system (air and water vapour mixing), which lowers the process air temperature and increases its relative humidity. As a consequence, it is necessary to reheat and dehumidify the air. The velocity and quality of drying is strongly influenced by the temperature and relative humidity of the drying air [22].

The drying of natural cork stoppers is carried out in natural drying systems, hot air ovens with forced circulation and vacuum ovens [4]. The hot air ovens usually integrate a drying compartment, a heating system and fans associated with the process air circuit. Some systems operate with a gas-based hot air generator (coupled burner and fan) where the stoppers move inside the drying compartment to reduce the drying time (lower heat consumption) and to subject the stoppers to more uniform conditions of drying [22]. To dry small batches of stoppers, static dryers (where the material is static inside the compartment) and fluidized bed dryers are used [22, 23, 24]. It is recommended that the drying air temperature is set between 40 and 55°C (during 30 minutes to 24 hours) [4]. In vacuum drying ovens, the pressure in the drying compartment is reduced and evaporation takes place at lower temperatures. Macedo, 1981 cited in [4] concludes that the drying process should be carried out in three steps, where the first and the second steps will be done under hot air conditions and the third step under a vacuum drying process. Solar dryers are also used, with reduced energy costs and high quality of drying [22].

The conditioned drying of cork planks may be necessary if they present a structural defect (acquired by cork naturally) called “greenery”. In this case, the planks have regions with very high humidity, 400 to 500% [22]. In such an event, a forced hot air oven is used to reduce the moisture content in these areas [22].

The cork granules, used as raw material in the production of agglomerates, need to have moisture content between 6 and 10% [4]. This is achieved through a drying process that normally uses a forced hot air circulation system. One of the most common systems is the rotary dryer that integrates a cylindrical or rotary drum in which the air is forced to circulate in counter current, i.e., in opposite direction to the movement of the granulate when drying through the cylinder [4]. The temperature of the drying air should be of the order of 150 °C and the air is heated in a steam or thermal oil heat exchanger [4]. The heat is usually produced in a combustion boiler. Another drying method used is the heating of the granules in silos [4]. Note that, depending on moisture content of the cork, it may be necessary to dry the material before and after the grinding process (see Figure 3). There are modern systems that perform drying and sterilization (reducing the TCA indices) of the cork granules in the same equipment [21].

Agglomeration. The heat treatment associated with the manufacture of composite agglomerates for coverings uses is usually carried out using heating air ovens or hyper-frequency systems [4]. The process temperature is usually between 110 and 150 ºC and the duration of the process between 4 and 22 hours, depending on the mixture of granules and binder [15, 4]. Another possible agglomeration process uses a heated platen (120-180ºC) press for 3 to 8 minutes [4].The heat treatment associated with the agglomeration process for the manufacture of agglomerated cork stoppers is very similar to that described above, however the recommended process temperature is between 100 and 130° C [4].

According to [4], the agglomeration of cork granulates for the production of black agglomerate should be carried out by means of a thermochemical treatment in autoclaves, since it allows to produce a more homogeneous material, with a lower cost of production and in a faster way. This treatment or "cure" is effected by the injection of superheated vapour at a temperature between 300 and 370 ° C, and a pressure of 30 to 60 kPa [4]. The curing time depends on the initial moisture content of the cork granules, the temperature of the process steam, and the mass and volume of granulates. For most cases, a time of 17 to 30 minutes is suitable [4].

Energy sources and consumption

[5] reports that in the Portuguese cork industry process heat is mostly produced in combustion boilers using several energy sources such as cork dust, firewood, forest residues and oil. It is also pointed out that, even though firewood and forest residues are used in the preparation and manufacture of all cork products, they are mainly used in the units that manufacture stoppers. Regarding cork powder residues, [5] reports that they are mainly consumed in the production of agglomerates, being the major fraction of cork powder produced during the granulation process. Electricity is mainly used for the operation of process equipment [5] and also used for process heat production using electric resistances during the agglomeration process [2]. Solar thermal systems for process heat production are now beginning to make part of the development strategy of some cork companies (e.g., [25]). The potential utilization and feasibility of biomass energy systems based on cork powder continues to be under analysis (e.g., [26]). To a certain extent, the cork industry in Portugal has been following the trend towards a paradigm shift in the use of energy sources strongly driven in the last decade by policies on energy, environment and sustainable development, together with specific legal measures concerning the rationalization of energy consumption, energy efficiency and renewable energy sources (See, for example [2, 26 and 27]).

In Portugal there is a leading business group in the cork industry sector [25]. Its first sustainability report [28] states that the company accounts for 30% of the world's cork processing and report a total energy consumption of 0.89 PJ for the year of 2005. It is stated in its most recent sustainability report [27] that the total energy consumption of the company in 2015 was about 1.37 PJ (this value only concerns to 70.1% of the economic activity of the business group), 65% of which was bioenergy (mainly cork powder), 28% electricity, 5% natural gas and the remaining 2% diesel and propane. One of the sustainability policies of the company is the use of cork residues, not suitable for the manufacture of cork product, for energy production in biomass boilers. In this context, a combined heat and power (CHP) system was installed in one of its production units that produces white cork agglomerate for coatings. The cogeneration system produces on average 9 TJ per year [27].

Recently, another Portuguese company carried out a study to investigate the economic viability of investing in a CHP system fired with cork powder and that comprised a boiler with a rotating pyrolytic burner. However, the results showed that viability was not achieved [29].

A study with the objective of developing and implementing an energy efficiency plan in production unit of agglomerated stoppers [2] brings together information about energy consumption in the facility. In this production unit an average of 400 million stoppers were produced each year. The sources of energy used were electricity (59%), natural gas (40%) and diesel (1%). Electricity was purchased from the grid. It is reported that the electricity consumption associated with the agglomeration process represents 51% of the total electricity consumed in the plant. Natural gas was used for process heat production and converted in combustion boilers, two boilers for steam generation and one other operating with a thermal fluid/oil as heat carrier. Heat was used for drying, agglomeration, steam injection sterilization, disk gluing and quality control processes. Diesel was consumed in a forklift truck. According to the monthly consumption data of natural gas and electricity during the years 2007 and

2008, the production unit consumed per month an average of 1.89 TJ of natural gas, and 4.27 TJ of electricity. It should be noted that these values comprise the energy consumed in the production and the energy consumed for other purposes, e.g., space heating, electricity for office equipment and lighting. The average monthly production of stoppers for the same period was 35.9 million. The industrial unit operated six days a week, 24 hours a day. The study considered that the energy load necessary for the operation of the production facilities (thermal and electric) was approximately constant.

Table 4. Data on consumption of primary energy sources and cork powder generation. Source: [12, 19, and 16]

	Natural cork stoppers	Champagne stoppers	Granulate for white agglomerate	Granulate for black agglomerate
Cork input (t)	13.8	16.9	1.55	1.54
Energy input				
Butane gas (kg)	1.5	-	-	-
Diesel oil (kg)	1955	1157	2.2	-
Electricity (GJ)	27.8	81.4	1327	1326
Cork powder (kg)	-	1528	8.6	-
Cork powder yield (%)		42*	34	35
Product output (t)	3.7	9	1	1

* cork powder with adhesives represents 10%

Based on several studies [19, 12, 16], Table 4 shows data on primary energy consumption and yields of cork powder obtained for different cork processing activities. For stoppers, the quantities produced correspond to 1 million, and for granulates the production was 1 t. The data were provided by the companies and in order to obtain representative data for each sector of activity the average values and the range of variability were calculated by the authors. The variability reflects, above all, the differences between the different companies (in the same activity) in the quantities of materials and energy required to obtain the final product.

The study concerning the manufacture of champagne stoppers includes five different companies [12]. The stoppers consist of a body made in cork agglomerate and two discs of natural cork and then the processing activity integrates the manufacture of granulate for the stopper body and the preparation of natural cork for the manufacture of disks. At the time of the study, only 21% of the cork dust generated was used for heat process corresponding to a direct replacement of 672 kg of diesel oil, having been considered a higher heating value (HHV) of 24.7 MJ/kg and 44.9 MJ kg for cork powder and for diesel oil respectively, and that the combustion system operates at a conversion efficiency of 80%. The study concluded that 2629 kg of cork powder would be required to completely replace diesel oil consumption, and that the potential for this replacement was enormous since the quantities of cork powder not used for the production of heat inside the factories themselves is very high (79%). Nevertheless, part of the waste is already being used in the filling of corks of less quality and/or to be channelled to external systems for use as an energy source. As a final note, it should be noted that the variability in energy consumption for the companies analysed was as follows: diesel oil, 11-434%; cork powder, 33-156%; electricity, 65-118%. Regarding the production of cork dust the variation around the mean value was about ± 10%.

The study that focuses on natural cork stoppers, includes the information of four different companies [16]. There is no reference to the generation of cork powder residues during the manufacture process however it was concluded that research must be carried out to evaluate the economic value or mass of the products and by-products generated. The considerations pointed out in the study which are relevant in terms of primary energy consumption for process heat production refer to diesel oil (554.8 kg consumed in the first boiling operation and 1072.1 kg in the second boiling operation). The study stresses that the environmental impact associated with the stage of manufacture of stoppers is quite high (reaching 65%), in particular the process associated with the second boiling, and therefore it is very important to evaluate the possibility of reducing consumption and/or replacement of the energy sources used.

The study regarding the production of cork granulates includes data from three different companies, all using standard technology [19]. With regard to the cork granulate for the production of white granulate, the study reports that 530.4 kg of cork powder is produced on average, but only 8.6 kg are used for energy production, in particular for process heat associated with the stage of preparation of the granulate that needs to be subjected to a boiling operation. As regards the production of granulated for black cork agglomerates, the only source of energy used was electricity. Although the potential for use cork powder as energy source is high, was pointed out that their utilization for energy production was still at an initial stage of implantation in the companies analysed. The reason why other companies in the sector were not doing so was that the capital cost of the investment was high.

As a final example another study [30] refers that 1.45 kg of cork powder and other cork residues (or 26.7 MJ) are required to produce 1 kg of black cork agglomerate. This accounts for 92.5% of the required energy; the remaining 7.5% relate to electricity consumption needs.

CORK POWDER-BASED HEAT GENERATION

The utilization of cork powder as an energy source has a strong potential given its properties for thermochemical conversion. Various types of cork powder are generated depending on the processing operation that gave rise to it and thus their properties are equally distinct. In the next paragraphs, this fuel is characterized. Also important for the energy valorisation of any fuel is the conversion technology. Among the various forms of heat production from biomass systems, thermochemical conversion by direct combustion of solid biomass continues to represent the most important route since this type of systems are widely diffused and marketed, and technology maturity status is high. A characterization of the most common technologies is also made.

Resource

When using solid biomass for energy purposes, it is fundamental to know and understand the feedstock characteristics and properties that are related to its use as a fuel. Among the different physical and chemical properties of solid biomass fuels, the following are considered relevant in terms of biomass thermochemical conversion: Elemental composition, ash and volatile matter content, heating value, bulk density and moisture content [31]. Table 5 presents, for different cork powders originated in different production activities a compilation of relevant properties in terms of thermochemical energy conversion.

Based on [32, 33, and 34], Table 6 lists the fundamental properties of various types of cork powder residues and that relevant to their use as a biomass fuel.

[33] Analysed three types of cork powder residues obtained from the Portuguese processing industry. The residues had origin during the production of cork agglomerate and generated in the operations of sawing (type 1: high-grain saw dust) and polishing of black agglomerate (type 2: low-grain sawdust), and, in the initial phase of the production of white agglomerate (type 3: sandpaper dust). Also, wood dust obtained from triturated wood residues (type 4) was analysed; this type of residue can be obtained from operations carried out in cork oak forests. All residues were sieved to obtained biomass powders with the following particle sizes: type 1 – 1mm; type 2 - 63 µm; type 3 - 2.5 mm; type 4 – 1 mm.

Table 5. Properties of diverse cork powder types. Source: [7]

Cork powder origin	Moisture content (% w/w)	Bulk density (kg/m^3)	Ash content (% w/w)	HHV (MJ/kg)	Particle size fraction <0.25mm (% w/w)
Grinding operations	14	261	3.7	18.87	30.2
Cleaning (impurity removal)	20	328	6.0	15.91	4.0
Granulometric separation	11	306	3.3	18.93	20.3
Agglomerated panels cutting/sanding	3	115	0.9	27.71	35.0
Agglomerated stoppers/disks rectification	5	82	0.9	26.76	27.3
Natural stoppers/disks rectification	8	73	2.0	-	100
Expanded cork agglomerated cutting/sanding	3	60	1.6	29.29	10
Mixture of the first 3 powders	12	233	-	-	49.9

[32] Present results for a residue also obtained from the Portuguese industry (type 5). The particle size distribution curve is given, revealing, for particle sizes of 0.05, 0.10, 0.25, 0.50, 1.0, 2.0 and 4.0 mm, a granulometric fraction of 3%, 8%, 18%, 34%, 49%, 94% and 100% respectively. The study also characterizes pine wood sawdust (type 6) with granulometric fraction of 6%, 20%, 57%, 86%, 97% and 100% for particle sizes of 0.25, 0.5, 1.0, 2.0, 4.0 and 8.0 mm, respectively.

The cork powder residues characterized in [34] have origin in the granulometric separation process that occurs during the manufacturing of cork granulates. The granulometry of three samples of cork powder was analysed. From the particle size distribution curves determined in the study, the following fractions are obtained: *i*) residue sample - type 7, 94% for particle size of 0.50 mm; *ii*) residue sample - type 8, 51% and 37% for particle sizes of 1.00 and 1.40 mm; *iii*) residue sample - type 9, 7%, 23% and 68% for particle sizes of 1.40, 2.00 and 2.80 mm.

Table 6. Properties of several types of cork powder residues. Source: [34, 35, and 36]

Properties	Type* 1	Type* 2	Type* 3	Type* 4	Type 5	Type 6	Type 7	Type 8	Type 9
Moisture content (% w.b.)	1.1	0.9	1.5	2.7			9.71	9.63	15.57
Bulk density (kg/m^3)	-	-	-	-	190 (d.b.)	210 (d.b.)	379.1 (w.b.)	323.4 (w.b.)	361.2 (w.b.)
Ultimate analysis (% d.b.)									
C	62.8	64.1	55.1	36.5	52.0	50.5	50.45	52.89	51.88
H	6.5	6.6	6.1	4.2	6.0	6.1	6.02	5.92	6.92
N	0.7	0.7	0.7	0.5	0.61	0.48	0.47	0.33	0.57
S	0.01	0.01	0.03	0.01	0.03	0.03	0.03	0.03	0.04
Cl	0.8	0.5	0.4	0.1	0.06	0.01	-	-	-
O**	29.19	28.09	37.67	58.69	-	-	-	-	-
Proximate analysis (% d.b.)									
Volatile matter	78.8	75.6	77.6	67.1	74.7	83.6	75.69	76.31	75.74
Fixed carbon	19.10	21.3	17.6	20.0	-	-	19.61	19.70	19.92
Ash content	1.0	2.2	3.3	10.2	4.4	0.9	4.70	3.99	4.34
Higher heating value (MJ/kg d.b)	28.8	30.4	24.7	15.2	21.9	20.8	21.41	23.64	21.43
Lower heating value (MJ/kg d.b)	-	-	-	-	20.6	19.5	20.08	22.33	19.90
Lower heating value (MJ/kg w.b)	-	-	-	-	-	-	18.13	20.18	16.81
Energy density	-	-	-	-	-	-	6.873	6.526	6.072

* It is not defined if the quantities are determined on a wet basis or dry basis; ** Determine by difference [33].

Conversion technology

Conversion route A – Suspended combustion. Suspension combustion (also denominated by pulverized combustion or entrained flow combustion) is a technology that uses a pulverized powdered solid fuel, mixed with air, which is injected into the furnace by using specific burners, generally designated by "dust" or "powder" burners/combustors [35]. Commercial burner design is based on flame stabilization techniques of swirling the staged jets of primary, secondary and tertiary air [36]. Certain models allow simultaneous or separate use of different fuels in the same burner [35].

According to [36], in order to achieve higher combustion efficiency, biomass combustion boilers operating with wood dust combustors and with lower capacities (up to 2MW) require wood powders with very small particle sizes (usually less than 1 mm) and flake-like and narrow shape, reduced moisture content (preferably not superior to 10%) and high volatile matter content (not inferior to 80%). The same author notes that pulverized wood fuels with higher particle size and moisture content can also be used depending on the thermal capacity of the system and if co-combustion techniques (with straw, coal and gas) are applied. When considering the adoption of a wood dust burner to use with another biomass powder it is necessary to take into account the problems that may arise from the slagging and ash formation, because technology design is focused on wood dust fuels [35].

Manufactures that commercialize proven technology for dust burners (see [37], [38], [39]) can cover a wide range of capacities, from a few hundred of kilowatts up to (at least) 100 MW. The burners are able to operate with several powdered biomass fuels, coal dust, fuel oil and gaseous fuels, and are designed for retrofitting of existing gas/fuel oil boilers and also for new boilers. Systems that integrate the burner, the boiler, equipment for fuel feeding and storage, and to control the system operation in an automatic manner are commercially available. They usually consist of a horizontal furnace with a water-fired tube system, a flue gas cleaning system (Cyclone or Electrostatic precipitator), a powdered biomass storage silo and a feeding system to transport and dose the powdered biomass fuel into the furnace.

Conversion route B – Fluidized bed combustion. In fluidized bed combustion (FBC), solid fossil fuels are fed into an inert material bed (e.g., sand, gravel, ash or limestone), which is fluidized by a gas, usually pre-heated air, injected from the bottom of the furnace at a sufficient velocity so that fuel particles flow out of the bed and start to behave like a fluid, acquiring a continuous movement inside the combustion chamber [40]. For this type of technology, the thermal power output varies typically between 1 MWth and 500 MWth [41]. Various types of solid biomass fuels can be used, yet fuel particles size should be less than 5 mm and higher than 2 mm (Williams, A. et al 2012, cited in [36]). With respect to fuel moisture content, fluidized bed combustion technology can operate until a level of 60% [42]. The efficiency of the FBC boilers ranges from 75% to 92% (HHV) [41, 43].

Conversion route C – Cyclone-type pyrolytic dust burner. In the technology in question, the powdered fuel is subject to a pyrolysis or devolatilization process within the cyclone chamber of the burner producing combustible gases such CH_4, H_2, CO, CO_2, H_2O, etc., as well as tar. After this, the gas is fed into the furnace section of the boiler where secondary and tertiary air is added, allowing a controlled combustion flame inside the furnace [35]. Manufactures that commercialize proven technology offers a capacity range between 0.5 and 25 MW and the design is suitable for retrofitting of existing coal/gas/fuel oil furnaces.

SUMMARY AND CONCLUSIONS

The following points summarize the main issues addressed in the document and indicate future research:

- Portuguese industry leads the primary production of cork and the international market in terms of the quantities exported and imported of cork and cork articles. The business volume of the processing activity in the Portuguese cork industry represented 89% of the total business volume in 2013. The manufacture of natural cork stoppers is the activity in the Portuguese cork processing industry that generates higher value in export sales (44%), followed by the manufacture of stoppers made of agglomerated cork (28%) and by the manufacture of agglomerated cork materials for construction (25%). The wine and construction markets are, therefore, the destination of 97% of the exports sales of the Portuguese cork industry.

- The main cork processing activities involve the preparation of raw cork boards, the manufacture of natural cork products, the production of cork granulates and the manufacture of agglomerated products. These activities integrate productive processes with high heat demand for example, the operations of boiling, drying and heat treatment in the agglomeration process. There are operations with process temperatures below 60ºC (drying of cork), with temperatures between 100 and 200ºC (boiling and heat treatment operations for the agglomeration of cork in the production of white agglomerate), and temperatures between 200 and 400ºC (heat treatment during the black agglomerate production process). The main thermal carries used are hot water, steam, thermal oil and hot air.

- The cork powder residues and their properties relevant for thermochemical conversion were characterized in the paper. Depending on the production process, cork powder yields may range from about 20 to 40%. The higher calorific value of the cork powder is in the range of 15 to 30 MJ/kg depending on the type of powder, and the bulk density takes values between approximately 60 and 379 kg/m^3.The technology for solid biomass combustion systems that convert cork powder is well proven and commercially available, and can cover a wide range of capacities. Dust combustors are more suitable for particle sizes less than 1 mm.

- Data on primary energy consumption were presented for the various cork processing activities. The breakdown of energy consumption by energy source and end use is, as far as possible, presented in a systematic way and it is possible to treat the data in order to estimate the specific energy consumption required for a certain process and/or processing activity.

- Much of the data presented on energy consumption in the cork industry is not disaggregated in terms of processes, and even when they are, the data refer to total energy consumption and not to the rate of energy consumption. Therefore, it is not possible to estimate in a reliable manner the thermal loads involved in the processes. The preliminary evaluation of the thermal power required for a given process or various thermal processes makes it possible to define the capacity of the heat generation system and, consequently, to estimate the investment costs, and operation and maintenance costs which are indispensable input data in the feasibility analysis. Future work for the compilation of this data should be done and/or developing theoretical models to estimate specific thermal loads required by the processes.

- The information gathered in this paper serves as a basis for the initial stages of a techno-economic feasibility analyses for investments in cork-based energy conversion systems in cork factories. In future research, other key factors and parameters need to be characterized; in particular, those related to the financial aspects and economic benefits of investment projects, such as investment costs, operation and maintenance costs (O&M) and cork powder properties related to air pollutant emission. As an indication, according to the data reported by IRENA [44], the capital cost associated with solid biomass combustion systems for small-scale applications in industry is 574 €/kW_{th} and the O&M costs are 30 €/kW_{th}. For large-scale applications, the same study refers that capital costs are 505 €/kW_{th} and the operation and maintenance costs are 26 €/kW_{th}. For a reliable investment analysis, the capital and O&M costs of the individual components of the system must be known. There is also a need to better understand the technological development of the Portuguese cork factories for better defining the objectives for the project investments. For example, among the different routes to exploit cork powder residues, on site pelletization are pointed to have several advantages: reduction costs in storage and in operation and maintenance, high energy density and better control of the combustion process [45].

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