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FLEXible operation of FB plants co-Firing LOw rank coal with renewable fuels compensating vRES

FLEX FLORES

Dissemination Level: Public

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Deliverable 1.2. – Report on available and promising crushing and feeding systems for LRC and biomass blends

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EXECUTIVE SUMMARY

Deliverable 1.2 describes the work undertaken in the framework of Task 1.2 regarding the available crushing and feeding systems for industrial scale fluidized bed reactors. A thorough review is conducted to examine existing industrially operating systems for fuel handling, which include size reduction and feeding to the boiler, taking into account that each fuel type has its unique features. The state-of-the-art is presented to supply the project with the required information for the appropriate selection of fuel handling equipment to be examined within the techno-economic evaluation of the project. Cost data are retrieved through the literature, contact with suppliers and manufacturers. Considerable feedback has been given by the Public Power Corporation Greece (PPC) regarding equipment requirements and pricing.

Circulating fluidized bed boilers technology is briefly described to conclude to the fuel handling requirements. The crushing and feeding systems are analyzed and discussed in terms of their capacity, operating conditions and handled fuels. Differences among the various crushing systems are presented, in terms of size reduction, energy requirements, particle top-size and final size, production ratio, dimensions, as well as prices. The comparison is crucial for the design of an appropriate and energy efficient comminution process and the establishment of the optimal conditions on the cost minimization of the coal fuel beneficiation process, consequently affecting availability and reliable operation of a power plant, while ensuring the required fuel quality.

NOMENCLATURE

BFBC	Bubbling Fluidized Bed Combustion
CFB	Circulating Fluidized Bed
CFBC	Circulating Fluidized Bed Combustion
DFC	Dense Friction Course
FB	Fluidized Bed
LRC	Low Rank Coal
RDF	Refuse Derived Fuels
RPM	Rounds Per Minute
SRF	Solid Recovered Fuels
TPH	Tonnes Per Hour

TABLE OF CONTENTS

FIGURES

TABLES

Outline of this report

This report consists of five sections including the Executive summary, which is presented at the beginning of the document. In the Introductory section (**Section 1**), the importance of fuel crushing, as part of its beneficiation process, is highlighted. Additional information retrieved from the literature, concerning the desired size of different materials that are usually fed in fluidized bed combustors, such as coal, biomass and limestone, is delivered. In the next section (**Section 2**), the state-of-the-art crushing systems of the abovementioned materials are presented. Then, **Section 3** focuses on the available feeding systems, such as screw, belt and conveyors etc. In both **Sections 2 and 3** apart from design specifications of the different technologies, data are presented concerning their capital costs. Finally, the Conclusion section (**Section 4**), based on the analysis delivered in **Sections 2 and 3**, concludes on which types of crushers –for each feedstock-, as well as which feeding systems combine the most advantages, mostly in terms of cost and design specifications and, thus, they are recommended for utilization in a co-firing industrial fluidized bed power plant.

1. Introduction

One of the most attractive characteristics of fluidized bed (FB) combustors (also referred to as boilers in this deliverable) is fuel flexibility, which means the ability to burn different kinds of combustible material, even lower grade fuels. One usual application of circulating fluidized bed combustion (CFBC) technology is combustion of a fuel blend comprising a primary (usually LRC) and a secondary fuel (usually woody or straw biomass). Apart from the fuel blend, a sorbent (e.g., limestone) material is inserted in the same furnace for in-situ sulfur oxides (SO_x) capture. After their injection, the solid particles are suspended in a stream of upwardly flowing air (60–70% of the total air), which enters the bottom of the furnace.

Particle size is an important variable of the fluidization process, affecting significantly the fluidization regime, combustion homogeneity, as well as mass and heat transfer [1]. More specifically, particle size reduction increases the reacting surface and, thus, improves the combustion efficiency (in the case of coal and biomass) and the mixing efficiency (in the case of limestone in a fluidized bed boiler). Additionally, a better fuel blend handling is achieved; smaller particles are easier to convey, store and transport, whilst larger particles could block the fuel preparation tank and feeder systems, causing a non-homogeneous fuel feeding [1]. Finally, size reduction beneficiates the material; for instance, in the case of coal, ash and moisture could be removed. Therefore, the first stage of the fuel blend handling, before its entrance into the combustor, should be its comminution, a process of breaking a large mass into fine particles.

In FB boilers, coal is crushed down to a size of 1–10 mm, depending on the rank of coal, type of fuel feed and fed into the combustion chamber [2]. The limestone feed sizes are typically within the range of 0–6 mm (with mean size of 1–3 mm) [3]. Considering biomass or waste based fuels, the feedstock particle size can be as big as 200 mm [2]. Size reduction to the same level as coal is not required due to the higher volatile content of biomass in combustion systems [4]. Alternatively, pelletized fuel or sawdust can be burned in a CFB without pre-processing. However, the literature suggests that size-reduced biomass produces a more stable flame, high burnout, and low CO_2-to-energy content and ash emissions, when compared to pellets and bales [5] and thus it should be preferred over the uncrushed one. The fuel/sorbent crusher, i.e. the machine that serves for the size reduction of the fuel/sorbent materials, is frequently located at the fuel receiving station [2].

Generally, size reduction is an energy intensive unit operation. It can be categorized into the coarse range (crushing) and the finer range (grinding) size reduction, with the first one requiring less energy than the second one [6]. During crusher or mill operation, only a small fraction of the energy is used for actual breakage, with the rest being absorbed by the machine and being lost. The total cost of the beneficiation procedure strongly depends on the efficiency of the comminution process. Therefore, designing an energy efficient comminution process plays an important role in the coal beneficiation process in minimizing cost. Selecting the appropriate grinding machine and establishing the optimal conditions are crucial to increase the efficiency of comminution [7].

In most cases, there are four methods of size reduction process; impact, attrition, shearing and compression. The first involves an instantaneous impact between moving objects, such as rotating drums etc. The second uses surface sliding of a solid particle over another surface. Finally, sizing reduction through shearing is caused by shear forces generated in a solid particle, whilst compression is caused when the solid material is trapped between two hard objects, moving towards each other.

2. Crushing systems

2.1. Coal/limestone crushers

Coal, received in the form of lignite at the power station, is typically crushed to below 10 mm in size and then fed into the fluidized bed boiler. The above size limit is not necessarily tight and could change depending on the operational experience of a specific power plant [8]. Equipment used for coal size reduction can be classified into three main categories: i. primary crushing, ii. secondary crushing and iii. grinding (also referred to as pulverizing in this deliverable) [9]. Among the available technologies, **cage mills, impactors, hammer mills, granulators, roll and jaw crushers** are the ones that are used for coal size reduction in fluidized bed reactors [10]. The same equipment can be also used for limestone crushing. On the other hand, forestry products go through chippers and shredders rather than crushers.

Pennsylvania Crusher has supplied about half of the fuel handling systems for the world's current fleet of CFB boilers, offering several kinds of crushers, and has picked up a share of CFBs currently being built or planned [11, 12]. Pulverizers are not required, as the coal enters the boiler rather coarse. As far as chippers are concerned, Jeffrey Specialty Equipment (also referred to as Jeffrey Rader Corp.) is one of the major providers [11, 12]. Wood chips can be blended with coal or petcoke before entering the boiler. These technologies are analyzed in the following sections [10].

2.1.1. Cage mills

2.1.1.1. General

Cage Mills are internally fed impactors that are used for crushing, or grinding of friable dry materials, such as coal, glass, grain, limestone, calcium carbonate, refractory materials and others. They have a high ratio of size reduction (40:1 to 50:1) after a single pass through their cages. Generally, the feed size that they can handle ranges from 600 mm to 1,580 mm in diameter [13]. Therefore, they can be utilized for both primary crushing and final sizing.

Cage mills operation is simple and is based on crushing of the material with the bars of a rotating cage. More specifically, the solid particles are guided to the cage center through a hopper and are crushed into smaller pieces by striking repeatedly with the spinning cage pins, against each other and against breaker plates at high speed. The product size is controlled by varying the spacing between the sleeves and adjusting the speed of the rotating cage. The operator predetermines the cage rotation speed. Furthermore, the feed size and the produced capacity can increase with increase of the cage mill size. A typical cage mill arrangement with only one moving part and is interior is depicted in Figure 1.

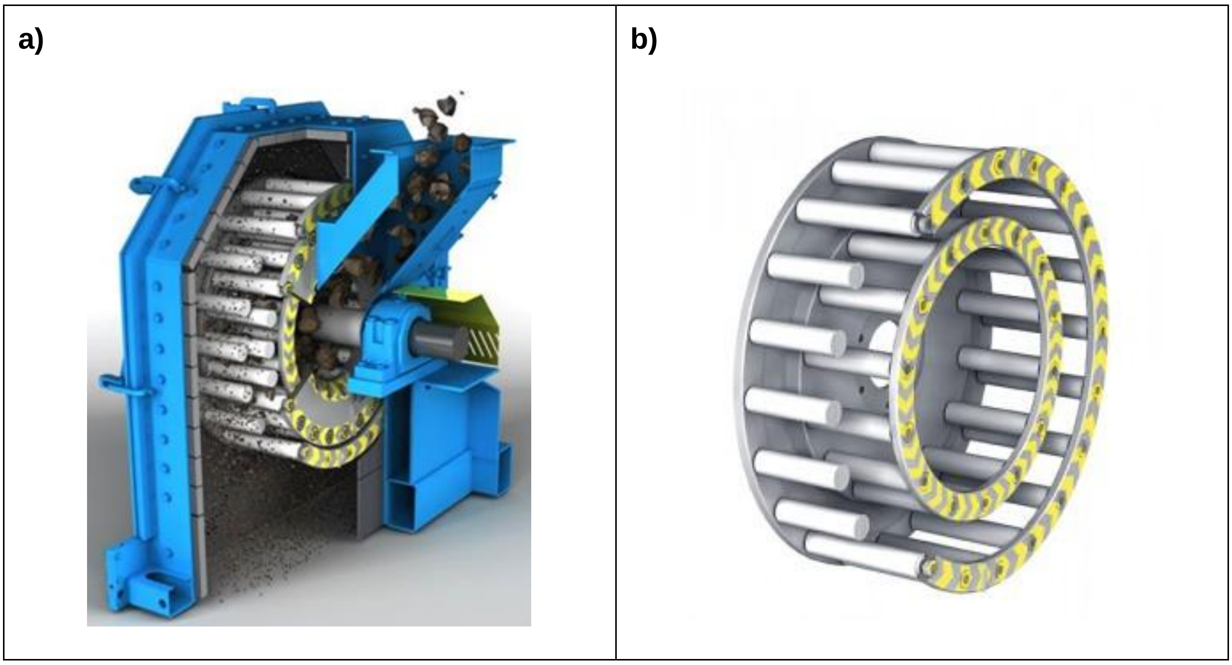


Figure 1. a) A typical cage mill arrangement with only one moving part (rotor) b) Interior of multi-row cage mill [14].

There are several types of commercial cage mills, with common operating principles. Generally, cage mills can be configured in single and multi (two, four, and six) row designs, each one with its own unique crushing applications:

i. Single row cage mills

Single row cage mills are usually utilized as secondary crushers for heavy-duty crushing, frequently of hard and highly abrasive materials. However, they can be used for size reduction of many kinds of materials. The largest cage mills available in the commerce nowadays can accept size as large as 450–500 mm and have a capacity of approximately 2,000 TPH (tonnes per hour). Normally, in typical applications the feed diameter size is 120–200 mm.

ii. Multi-row cage mills

In multi-row cage mills, the cages are arranged concentrically. Each cage spins in the opposite direction from that of the cage adjacent to it. The most known cage mill brands are Stedman cage mills [13], followed by Gundlach cage mills [15]. Description of a few commercial cage mill models follow.

2.1.1.2. Stedman machine cage mills

Stedman's inventory of multi-cage mills and pulverizers includes the H-Series, F-Series for sticky, high moisture and the Y-Series designed for less abrasive material applications [16], Figure 2.

More specifically, the H-Series cage mill [17] can grind, crush and mix, both abrasive and non-abrasive feed material, wet, sticky or dry, ranging from 19 to 64 mm in size. The final product can be finer (almost 12 mm) and more uniform grind compared to the rest of the cage mill types. Such types of mills are reversible, thus having an extended wear life, and can accommodate two-, four-, or six-row cage assemblies. Their two row version can handle from 35 to 240 TPH.

The F-Series cage mill [18] includes a flared discharge opening that can efficiently crush the wettest and stickiest of available materials without clogging or plugging problems. The input feed size that an F-Series mill can handle ranges from 19 to 90 mm. Its unique design allows for a variety of high-moisture sticky materials to be reduced with less downtime for cleaning compared to other size reduction mills.

Finally, the Y-Series [19] is a controlled-impact, multi-cage mill designed for crushing thousands of less abrasive materials, including wet and tacky materials. This type of crusher should be preferred when large capacity, high-yield, and a uniform particle size is required. The main reason for selecting such a crusher is that this is an economical one in terms of maintenance cost, since it has no hammers or screens to replace and an open discharge that won’t plug.

Figure 2. Stedman cage mills [16].

2.1.1.3. Gundlach Cage-Paktor cage mill

Gundlach Cage-Paktor [15] has multiple rows of impact bars to offer selective stages of reduction, without the need of extra screens, reducing, thus, its maintenance cost. It is appropriate for crushing oversized wet, sticky or difficult-to-crush materials and has a high reduction ratio –sizes of up to 100 m can be crushed down to 2mm. Due to its selective crushing requires lower horsepower, compared to traditional cage mills, having thus, a lower operational cost.

In a Gundlach Cage-Paktor, material enters directly into the center innermost cage through the low-friction inlet (or feed chute). As they pass through the rotating cage, only oversized particles large enough in mass are crushed. Already-to-size particles from previous stages of reduction are not reduced, so less fines are created. At the same time, multiple stages of crushing inside the mill minimize product oversize, achieving greater crushing efficiency and more finished product in the desired size range. Figure 3 depicts the interior design and the basic operation of a Gundlach Cage-Paktor.

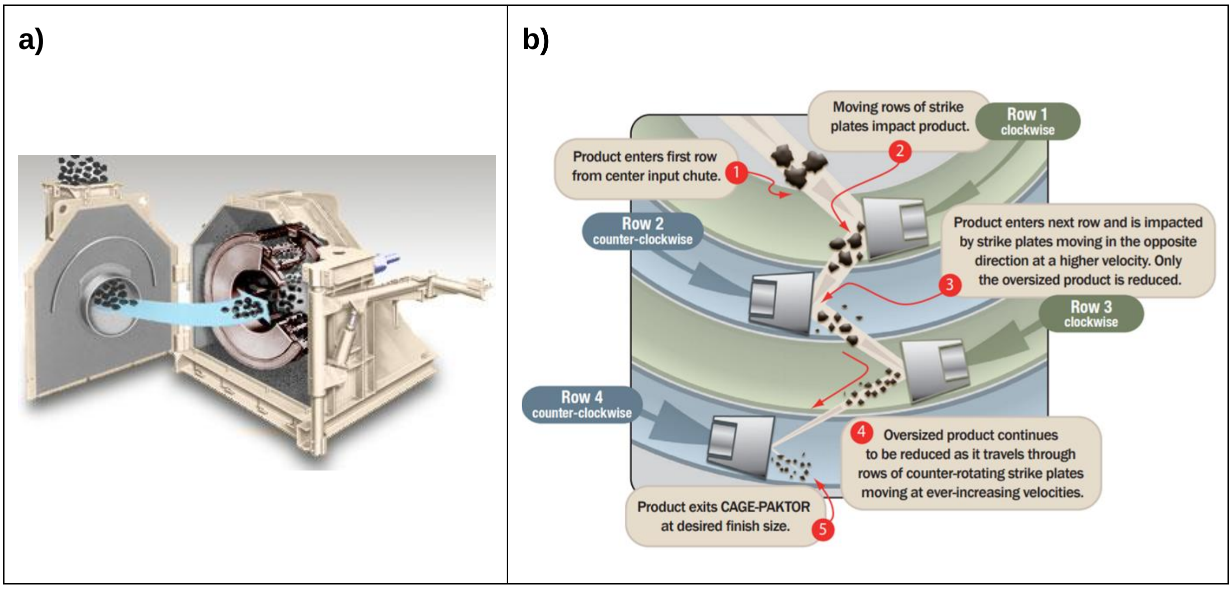


Figure 3. Gundlach Cage-Paktor a) design and b) basic operation [15].

Basic design specifications of Cage-Paktor Cage mill are presented in Table 1.

Table 1. Specifications of a typical Cage-mill [15].

Specifications	
MODEL 401C3R Cage-Paktor Cage mill	
Typical particle Top-size [mm]	57
Max. reduction ratio	50:1
Max. feed capacity [TPH]	135
Number of rotating cages	2
Number of rows of striking surfaces	4
Chamber dimensions W x D x H [mm]	1,880 x 2,261 x 1,626
Estimated shipping weight [kg]	4,105

2.1.2. Impactors

2.1.2.1. General

Impactors incorporate striking to pulverize material [10]. They are mainly used for final sizing of limestone, dolomite, coal etc., with an optimum percentage of products below 3 mm size and with a minimum amount of fines. However, depending on the manufacturer, they can be used for primary and secondary sizing, as well. The modern impactors can maintain their throughput with wet coals and are able to pass non-crushable through. Their rotors can usually be run in either direction to provide equal wear on both hammer surfaces (reversible impactors). They are mostly utilized in fields, such as metallurgy, chemical engineering, building materials etc. Impactors are mainly categorized in vertical shaft impact crushers (VSIC) and horizontal shaft impact crushers (HSIC). The following sections present impact crushers from Pennsylvania and Tesab, leading manufacturers of the industry.

2.1.2.2. Penssylvania reversible impactor

Pennsylvania Crusher reversible impactors [20] utilize free-air impact to crush materials along natural fault lines and an open-bottom design to evacuate material quickly. Their main advantage over conventional impactors is that they have less wear on their hammers and breaker blocks, due to their reversible rotation. They have high reduction ratios –up to 35:1- and produce materials of cubical shape. Additionally, they achieve fewer fines consume less horsepower per ton than hammer mills. There are two types of reversible impactors from Pennsylvania Crusher brand, the CAL –with high reduction ratio 35:1- and the CXC –with moderate reduction ratio 16:1- series. Additionally, from the same manufacturer there is available the Pennsylvania coalpaktor that is better suited for the needs of a coal fired FB plant, as it will be analyzed in the following section.

2.1.2.3. Pennsylvania coalpactor

Coalpactors manufactured by Pennsylvania crusher brand, are reversible type of impactors, which can be mainly used for the size reduction of **wet or low grades of coal** — such as lignite [21]. Such type of crushers are ideally suited for fluidized bed (FB) boiler plants. They can also be implemented on crushing of metallurgical coal for coke production. Apart from this, owing to their open-bottom design overcrushing is prevented (Figure 4). Finally, reversible rotor equalizes wear on hammers and breaker blocks and extends part life, reducing, thus, their maintenance cost.

a) b)

Figure 4. Pennsylvania coalpactor a) Outside and b) Inside view [21].

2.1.2.4. Tesab mobile impact crushers

Tesab impact crushers [22] are compact, mobile machines, suitable for sizing of coal and limestone at a good cubical shape and high reduction rate (up to 20:1) at a low cost. Such type of impactor integrates a caterpillar cylinder engine for a fuel-efficient performance and is more suitable for crashing the material near its mining area. Depending on its model, Tesab impactors can be used either for primary, secondary or tertiary sizing. Additionally, the production rate varies from 150 to 350 TPH. A few of the design specifications found are presented in Table 2.

Table 2. Specifications of typical impact crushers [22].

Specifications			
	Primary impactors	**Secondary impactors**	**Tertiary impactors**
Models	**1012TS, 1012T**	**623CT, 1412T, 1012T**	**1412T, 623CT**
Particle Top-size [mm]	400–500	20–150	20–65
Final size [mm]	0–75	0–45	0–20
Typical reduction ratio	6:1	4:1	3:1
Max. reduction ratio	20:1	20:1	20:1
Feed capacity [TPH]	250–350	150–350	150–350
Dimensions W x L [mm]	2,900 x 15,700*	3,850 x 17,030 **	2,900 x 16,130***
Estimated shipping weight [kg]	45,200	42,700	26,350

*referring to 1012TS model
**referring to 1412T model
***referring to 623CT model

2.1.3. Hammer mills

2.1.3.1. General

Hammer mills are impact-type crushers that are mainly used for grinding (grinding refers to significant particle size reduction) through a two-step process. In the first step, the material is reduced by dynamic impact as it passes through hammers rotating at high velocity. In the second step, which is done for the final product sizing, crushing occurs by attrition and shear in a small clearance between the hammers and a perforated grate section or screen bars. This grate section, which the material must pass through (Figure 5) is the main difference of a hammer mill from an impactor; the latter simply having an open bottom, where material exits after its crushing process. Therefore, the product size is highly dependent upon the i) rotor speed, ii) grinding plate setting, iii) number, size and type of hammers and iv) size of openings in the screens or grate bars. Typical output sizes range from 25.4 mm (1”) to 6.35 mm (¼”). Aside from grinding, hammer mills can be used for coarse granulations, crack grain and to homogenize mixtures of materials [23].

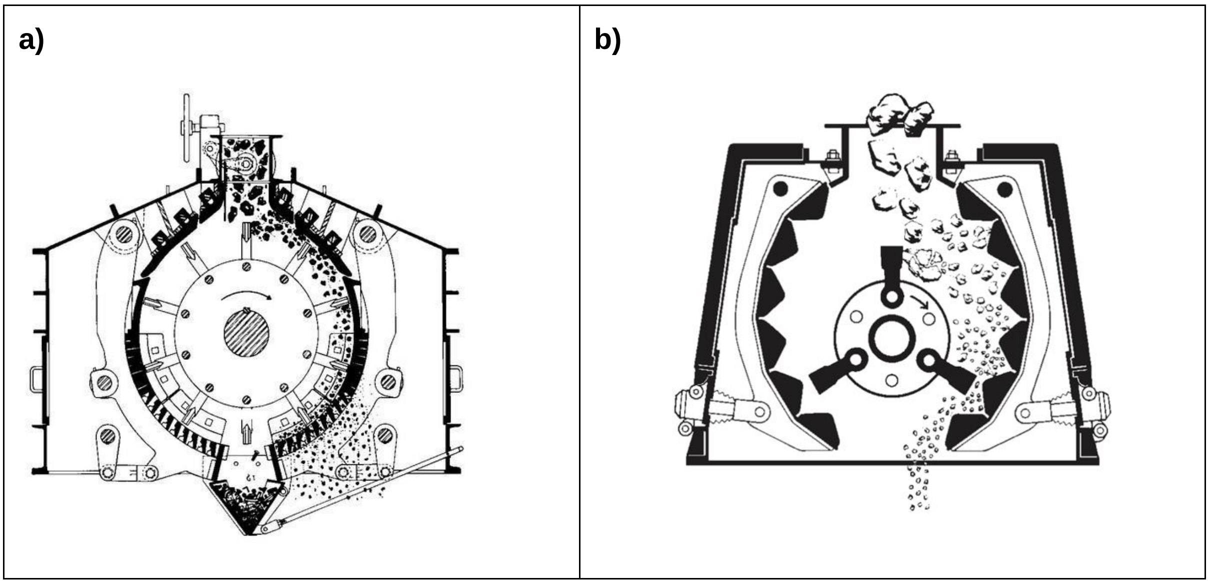


Figure 5. Difference between a) reversible hammer mill and b) reversible impactor [24].

The main advantage of hammer mills compared to other types of sizing equipment is that the final product has a high size uniformity with a minimum percentage of oversized particles. The key factors in determining the consistency of the finished particle size are the grate section and screen bars. More specifically, the grate openings allow the finer material to be discharged, while retaining oversized material for further crushing. However, this leads to a high inter-particle, particle-hammer and particle-wall shear force that produces a substantial amount of fines and a subsequent wear of the grates and the hammers. State-of-the-art systems use a reversible hammer to increase the time between maintenance shutdowns and to maximize the hammer wear life [6]. **This major drawback of a hammer mill is not so important for the crushing of lignite, which is generally softer than high-rank coal [7]**. It should be noted that, apart from coal, hammer mills have a wide application in biomass size reduction, such as straw, wood pellets etc., because of their simple design, ruggedness and versatility.

2.1.3.2. Pennsylvania one-way hammer mill

One-way hammer mills, Figure 6, are used for both primary and secondary sizing of a wide range of materials — mildly to non-abrasive, like coal, limestone, sand molds etc. — to various output sizes in a single pass. Depending on the type of the hammer mill, the output size ranges from 38.1–127 mm (DFC Hammer Mills for primary crushing) to 6.4–38.1 mm (type T and type JRT hammer mills for secondary crushing). Pennsylvania one-way hammer mill employs three distinct and highly effective crushing actions: impact, shear and attrition. It shows excellent control of top-size, while trapping uncrushable in tramp iron pocket [25].

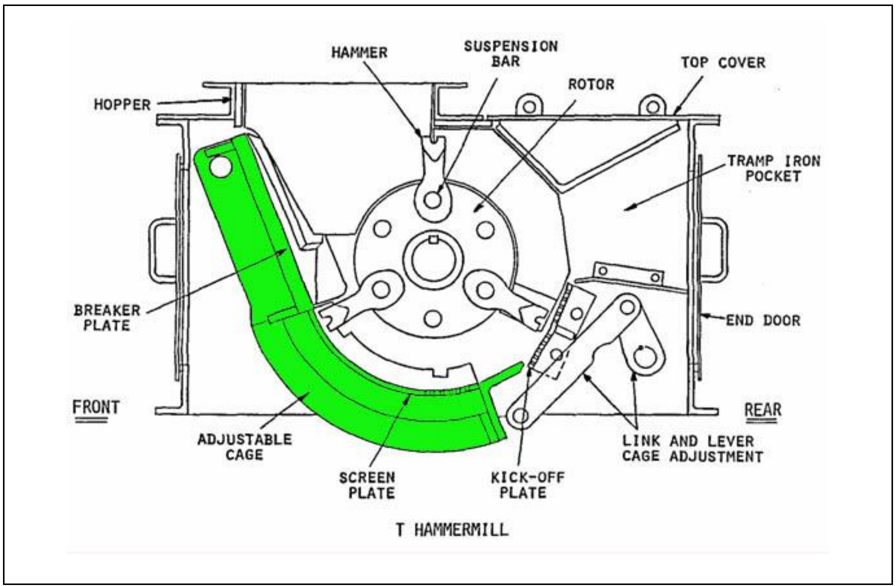


Figure 6. Type T one-way hammer mill schematic drawing [26].

A few of the design specifications of model type T one-way hammer mill found are presented in Table 3.

Table 3. Specifications of typical one-way hammer mill [26].

Specifications	
MODEL type T2-24B	
Particle Top-size [mm]	152
Max. reduction ratio	25:1
Max. feed capacity [TPH]	150
Grinding elements	Hammers
Grinding media	Forded steel/cast manganese steel
Hopper dimensions W x D [mm]	460 x 711
Max. rotor speed [RPM]	1,800 Direct connect 1,500 V-belt driven

2.1.3.3. Pennsylvania FBR reversible hammer mill

This type of hammer mill (Figure 7) is best suited for crushing materials that can be fed into a fluidized bed boiler, such as coal, limestone and biomass (woody, wheat, barley etc.). It has low cost (operating, maintenance, capital) and better performance compared to other types of crushers that are far more expensive. Specifically, its operating cost is low due to its relatively low power requirements and its maintenance is minimized due to less wear in its hammers. Unlike some light duty crushers offered today which were designed to crush non-mineral products, the FBR model is very rugged and can crush a wide range of hard materials [27].

a) **b)**

Figure 7. Pennsylvania reversible hammer mill a) Exterior and b) Interior part [28].

Similar to a traditional reversible hammer mill the FBR model has a symmetrical crushing chamber and a reversed rotor assembly. Owing to the reversed rotor movement the material can be crushed either to the one side of the chamber or to the other. This movement produces uniform wear on both working surfaces of the hammer, keeping its edges sharp and producing a consistently uniform output size. The need to shut down and manually inverse the hammers as required by the one-way crushers is eliminated. Another advantage is the extended time-between-changes, — about twice that of one-way crushers — provided by the other crushing components (breaker blocks, screen plate or screen bars) that are double in number. One similar model of this type of mill offers air connection for pneumatic handling of the product — this can be found in Williams patent crusher and pulverizer reversible hammer mills [29].

2.1.3.4. Holmes hammer mill coal crusher

Holmes Hammer Mill coal crushers can be used for sizing of bulk samples of coal and coke with rotary-swing hammers. The enclosed cases, covered feed hoppers, and rugged cast iron housings ensure safe and efficient operation with low maintenance. Feed hopper gates enable manual feed control (Figure 8).

Figure 8. Holmes hammer mill [30].

Hinged and latched housings offer quick access to the grinding chamber for cleaning and replacement of the bolted-in screens. The open-latch sensor cuts all power for increased safety and rotors, swing hammers and screen plates larger than 4.8 mm (3/16 in) are heat-treated and hardened to promote maximum service life (Table 4). Spring-loaded clamps help seal sample collection containers to discharge spouts for dust control during operation.

Units are mounted on four casters for easy relocation in the lab. The standard special control box contains NEMA 12 magnetic starter and over-load protection, wiring running at 230V/60Hz, 3-phase.

Table 4. Specifications of a typical Holmes hammer mill [30].

Specifications	
Particle Top-size [mm]	152
Final size [mm]	4.75
Max. feed capacity [TPH]	1.8
Grinding elements	Swing hammers
Grinding media	Manganese Steel
Chamber dimensions W x D x H [mm]	915 x 990 x 1,422
Estimated shipping weight [kg]	362.88

2.1.4. Granulators

2.1.4.1. General

Granulators are one-way hammer mills that can be used for either primary or final crushing. Their operation is based on a combination of impact and rolling compression, using rows of ring hammers that crush the feed material with a slow, positive rolling action [10, 11]. Granulators are operated generally at slow speed, i.e. 3,000–9,000 fpm and have a typical reduction ratio of 10:1. The **input size is usually 150 mm** (maximum size can reach up to 500 mm) and the **output top-size ranges from 12 to 50 mm**. Crushing action involves minimum attrition and, thus, produces minimum fines. The product size is determined by screen openings and is adjusted by changing the clearance between the cage and the path of the ring hammers. The main advantage of such machines is that they can handle wet, frozen, fine and dirty coals with ease. They can be used for coal crushing both for its preparation before its entrance into the boiler and for its intermediate storage.

As can be seen from Figure 9a, in a coal Granulator, coal flows through the feed opening directly into the path of the ring hammers. In this path, the material is primarily crushed through impact and is driven against the breaker plate for a further reduction. Final sizing occurs by the rolling compression of the ring hammers as the coal passes over the screen plate [25].

The most widely installed granulator in the world is the Pennsylvania TKK Koal-King Granulator model that can crash a given material in one pass, Figure 9b, and with a minimum of additional fines [31]. Even in harsh weather conditions, such as extreme cold, this crusher can reduce frozen lumps of coal. Apart from this, this model offers servicing and maintenance advantages — split of bearing housing arrangements for an easier flushing and lubrication, additional by-pass chute to prevent unnecessary wear from oversized coal etc. — that enable cost savings throughout its long service life [32]. Table 5 presents design specifications of a typical TKK Granulator.

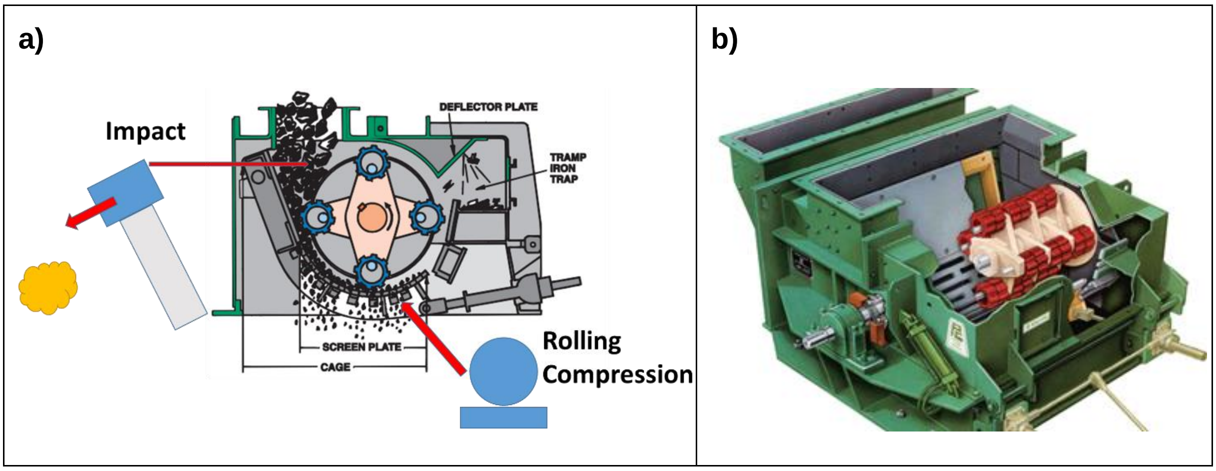


Figure 9. a) Granulator crusher operation, b) TKK Koal-King Granulator [32].

Table 5. Specifications of a typical Granulator [25].

Specifications	
MODEL TKK 26 KOAL-KING GRANULATOR	
Particle Top-size [mm]	254*
Typical reduction ratio	10:1
Max. feed capacity [TPH]	150**
Chamber dimensions W x D x H [mm]	1,467 x 1,574.8 x 800
Estimated shipping weight [kg]	1,814
Typical rotor speed [RPM]	720
Max. rotor speed [RPM]	1,185
Approximate horsepower [HP]	60-150

* Other models of this company accept input sizes of up to 457 mm [31].

** In other models can be an order of magnitude higher [33].

2.1.5. Roll crushers

2.1.5.1. General

Roll crushers are compression type crushers that are mostly used for crushing of washed coal — i.e. coal that has been mechanically washed off impurities, such as ash, soil, rocks etc. — in coal mines, power plants and refineries. Additionally, they can be utilized for size reduction of any other friable, sticky, frozen and less abrasive feed, such as salt, glass, sand and fluidized bed boiler sorbents, including limestone and dolomite. A roll crusher uses two or more cylinders (or drums) connected to counter-rotating horizontal shafts. As the material passes through the cylinders, a finer and smaller product is created.

Roll crushers are mainly categorized into single roll against a breaker plate, single stage 2-roll, and two-stage 4-roll crushers. The choice among them depends upon the type of feed material, feed and desired product size and consistency of both feed and product [29]. The crusher's capacity is determined by the roll gap, length and speed of the roll. Generally, single roll crushers have higher reduction ratio, capacity and can handle higher feed sizes than multiple ones. Therefore, single roll crushers are mostly used for primary crushing and multi-roll crushers for final sizing.

Roll crushers are usually choke-fed from hoppers. Alternatively, they can be fed at continuous, controlled rates from vibratory screens, apron feeders or belts. Finally, the product material is removed from the bottom of the crusher and fed into the fluidized bed boiler with belt conveyors. It should be noted that the size of the belt and its speed must be matched to the crusher capacity, even for occasions, where a huge volume of input material may simply flow through the crusher at a high rate.

2.1.5.2. Single roll crushers

Single roll crushers are crushers, of simple construction and operation, with a reduction ratio of up to 6:1. Such crushers can reduce large size particles to a medium size with a single pass and a low roll speed — 50 to 60 RPM. Therefore, the percentage of fines produced is minimized and the power demand of the crusher is low. They are also called lump breakers, as they can be used for breaking, apart from washed coal, frozen or agglomerated materials.

Single roll crushers' operation is based on impact, shear and compression, by simply using a breaker plate, which is adjustable, and a revolving roll. Initially, crushing occurs from impact of the material with the teeth of the revolving roll, Figure 10a. Later on, the material is further broken into smaller pieces, by the shearing action of the roll teeth and by compression against the breaker plate.

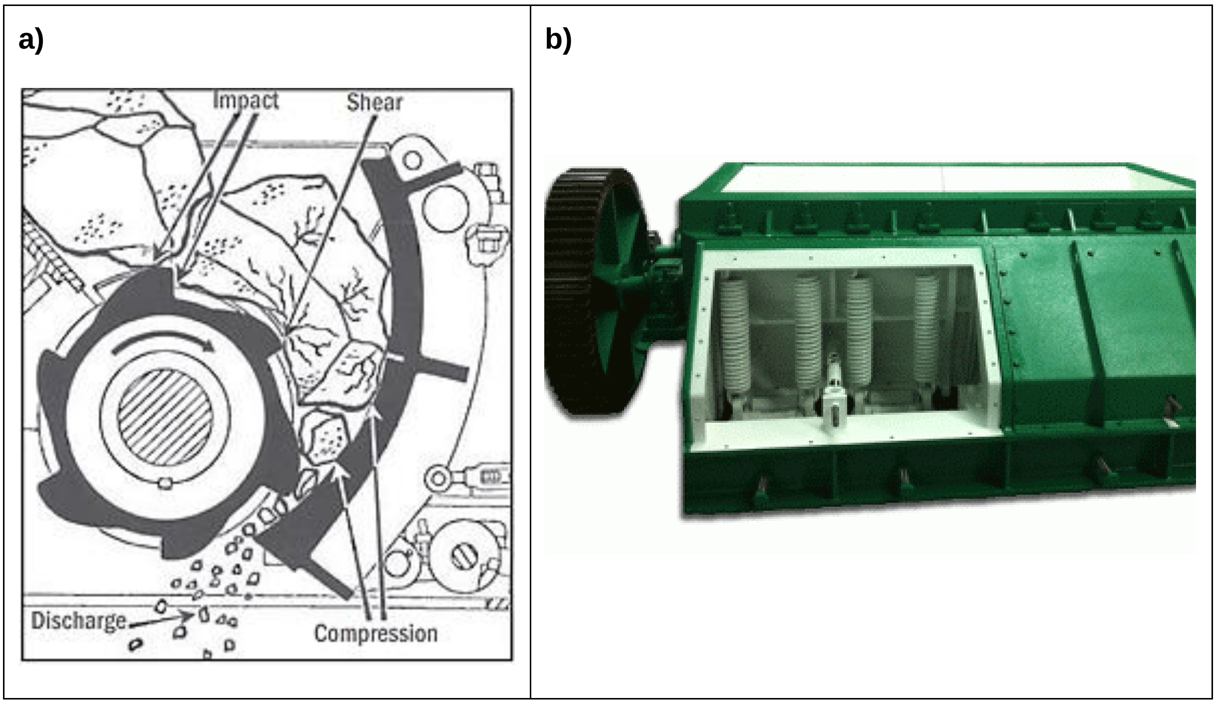


Figure 10. a) Single roll crusher operation, b) Pennsylvania Crusher Type K single roll crusher [25].

Pennsylvania brand single roll crushers are the most known crushers worldwide [34]. Such crushers are available in a variety of models, with product sizes ranging from 76 mm to 305 mm. Amongst them, the most commonly used is the Type K crusher, which is suited for the size reduction of materials having a compressive strength of 8,000 psi or less [25]. Another company that supplies single roll crushers is Williams Patent crusher and pulverizer Co [29].

2.1.5.3. Multi-roll crushers

Multi-roll crushers reduce size primarily through compression, although some shear is obtained with toothed rolls. Multi-roll crushers mainly comprise two or four counter-rotating rolls that grab and compress the solid material. The product size is determined by the gap between the rolls. Owing to the fact that such crushers have a relatively low maximum reduction ratio —equal to 4:1 for single stage 2-roll (S) series— the input size cannot be higher than four times the rolls gap (Figure 11). One of their major advantages is that they give a very fine product size distribution and they produce very little dust or fines. This is the reason why they are mostly used for final sizing. Added to this, they can be effective for crushing hard or resilient coal.

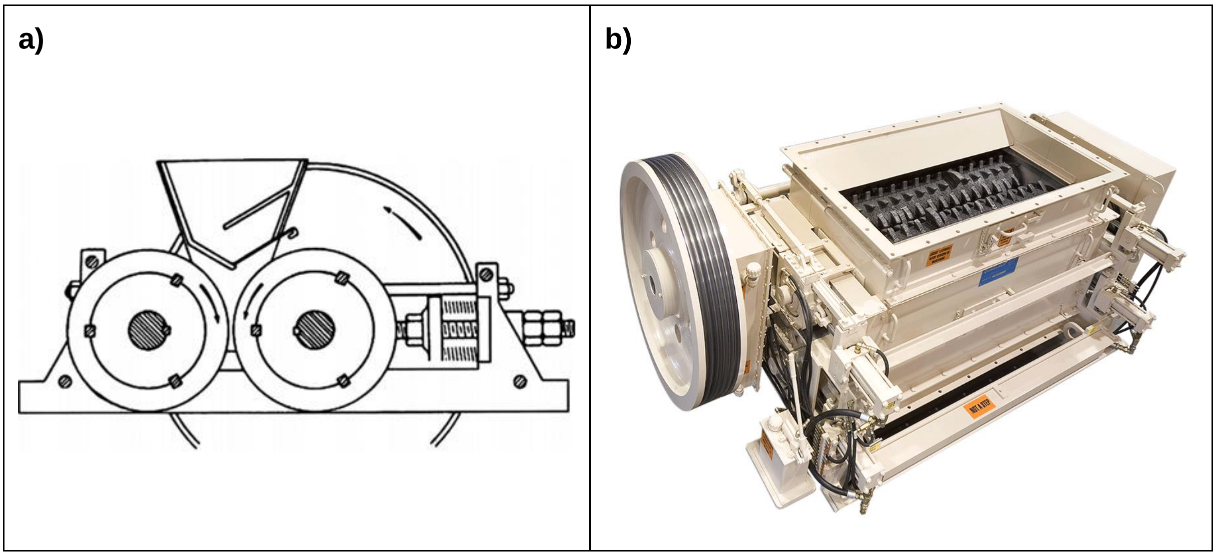


Figure 11. a) Double roll crusher operation [9] and b) Upper view of multi-roll crusher by Gundlach crushers brand [35].

Gundlach multi-roll crushers, Figure 11, are mostly installed in power plants as they offer a series of advantages, such as uniform product sizing, low horsepower and slow roll speed. Apart from single stage roll crushers, this company offers double stage four roll crushers, with higher reduction ratios – up to 16:1. In Table 6 are presented design specifications of typical multi-roll crushers manufactured by Gundlach Crushers brand.

Table 6. Specifications of typical multi-roll crushers (manufactured by Gundlach Crushers brand) [35].

Specifications		
	4060D Double Stage, Four Roll Crusher	**4060S Single Stage, Double Roll Crusher**
Material	Limestone	Lignite
Particle Top-size [mm]	<100	100–200
Feed size [mm]	100–800	95% passing 800
Bulk density [kg·m^{-3}]	1,350	1,350
Max. feed capacity [TPH]	60	200
Chamber dimensions W x D x H [mm]	1,575 x 2,438 x 2,029	1,575 x 1,740 x 1,108
Estimated shipping weight [kg]	14,062	6,804
Typical rotor speed [RPM]	1,000	1,000
Max. rotor speed [RPM]	1,200	1,200
Approximate horsepower [HP]	75	40

2.1.6. Jaw Crushers

2.1.6.1. General

Jaw Crushers are primary crushers that are mostly used for size reduction of unusually hard, tough and/or abrasive rock, ferroalloys and glass, which cause excessive wear to the other types of crushers analyzed. Additionally, they can be used for crushing of limestone and dolomite. They are desirable for portable applications and therefore they can be utilized for coal primary sizing near the mine.

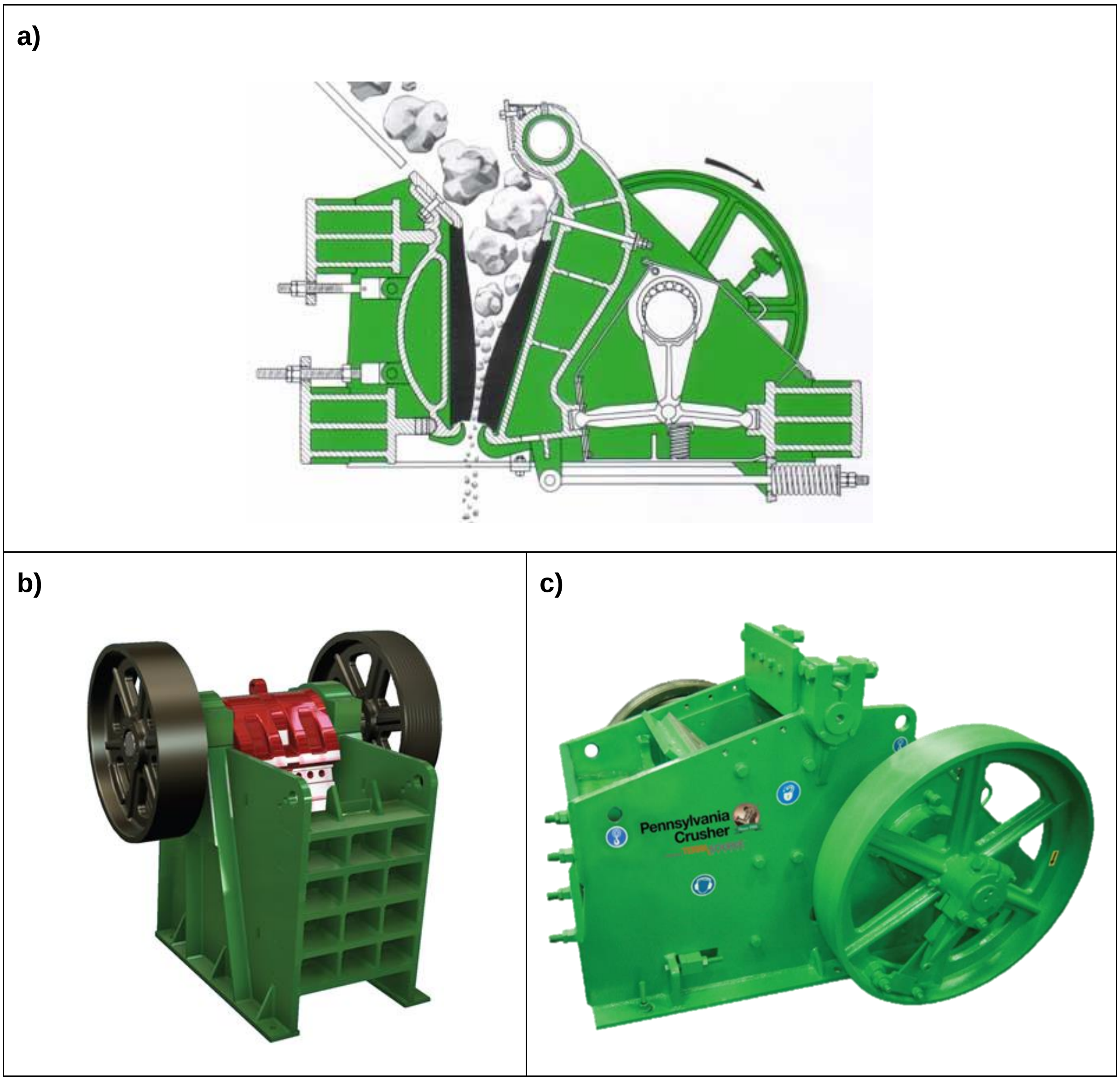


Figure 12. a) Jaw crusher basic operation, b) Single toggle (Overhead eccentric) and c) Double toggle jaw crusher [36], [37].

Jaw Crushers crush by compression of the material between two opposing surfaces — the jaws. Some of their advantages are minimal abrasion or gouging of the jaw plates, often less than 25% of other jaws, relatively low fines production, desirable for portable applications, strictly compression crushing which provides longer jaw service life, minimal dusting [17]. They can be found in the market in both Double Toggle and Overhead eccentric models, Figure 12, with a reduction ratio of up to 7:1 for both styles. Typical speeds found in the literature are 300 to 390 RPM for the Double Toggle units and 200 to 300 RPM for the Overhead eccentric units. They can generally handle materials as large as 700-1,000 mm, depending on the model used (Table 7).

The PEW Series Euro-style jaw crushers [38] are new Overhead eccentric high-efficiency hydraulic control jaw crushers developed on basis of international advanced technology for jaw crusher free of such defects of the common jaw crushers as poor performance, cumbersomeness and complex. The PEW series Euro-style jaw crushers have adopted the international advanced technology of the V-shaped crushing cavity, the brand-new frame and movable jaw structure and the hydraulic adjustment and centralized automatic lubrication. Apart from these crushers, Pennsylvania crushers are famous on a global basis [37].

Table 7. Specifications of Jaw Crusher PEW860 by SBM Solution [38].

Specifications	
Model	PEW860
Feeding opening (mm)	860 x 1,100
Max. Feed size (mm)	720
Max. reduction ratio	7:1
Feed Capacity (TPH)	200-500
Power (kW)	132
Overall dimension W x D x H (mm)	3,300 x 2,320 x 3,120

2.2. Biomass size reduction equipment

Regarding biomass size reduction, different types are discussed and contrasted in short in this section. Roughly biomass is classified into harvested and non-harvested [8]. The first category includes long and slender biomass with high amounts of moisture usually in the form of bales, such as straw (wheat, rice etc.), grass and bagasse. The second category comprises woodchips, rice husk, bark and prunnings. The latter category is not as long as the first one and often comes in a granular shape –in the case of rice husk or coffee beans. Depending on the biomass type, different size reduction equipment is used. Each type of size reduction equipment has variations in how material is fed through the equipment, speed of operation, and several other design characteristics [39].

Harvested biomass is reduced in size with shredders [8]. The equipment for woody biomass size reduction includes chippers, and shredders, used for primary sizing, as well as grinders for final size reduction similar with the equipment for coal beneficiation, such as hammer mills or usually called wood/bark hogs for the case of biomass (discussed in section 2.1.3) [8]. More specifically, the product size depending on the equipment used is 50-250 mm for chunkers, 5-50 mm for chippers and less than 80 mm for hammer mills [40]. Generally, chippers slice the wood fiber, whilst hogs and shredders reduce the wood particles through impact. Apart from these, there are hybrid machines that deploy a combination of the tooling mentioned above. Finally, refuse shredders are utilized for size reduction of refuse derived fuels.

2.2.1. Wood chippers

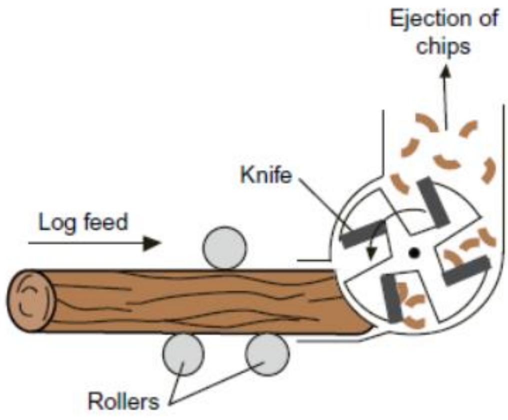
2.2.1.1. General

A wood (or tree) chipper is a machine used for size reduction of wood (mostly of tree limbs or trunks) into smaller woodchips. The final product has two surfaces and clean edges of specified dimensions. Wood chips are larger pieces (0–100 mm) from forest residues made by cutting or chipping (Figure 13). They are low cost, as a waste material that does not undergo expensive treatment steps. A downside of wood chips is that they have a higher moisture content (41–51 %), a lower energy content (14–17 GJ/tonne) and a lower bulk density (209–273 $kg \cdot m^{-3}$) in comparison to the other solid biomass types [41].

Figure 13. Wood chips [41]

Wood chippers are classified into disc and drum chippers, Figure 14. In a disc chipper, the wood is fed from the side, meeting a large rotating disc with several knives; as it passes past the disc, it is cut into smaller pieces. In a drum chipper, several knives are embedded in grooves of a rotating drum, which chips the fed wood. The chips, are carried away and thrown to the other end by the grooves [40]. The product material is uniform in size.

a)



b)

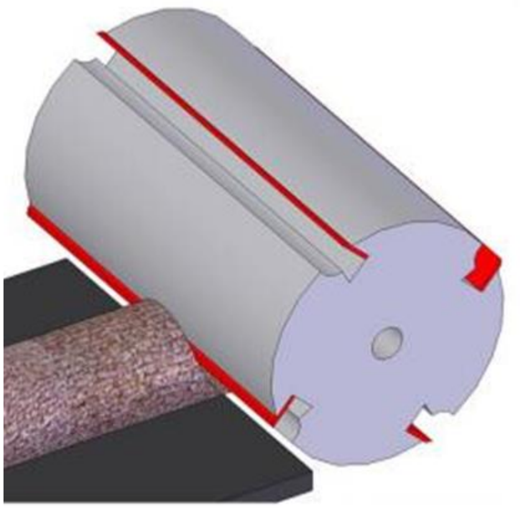
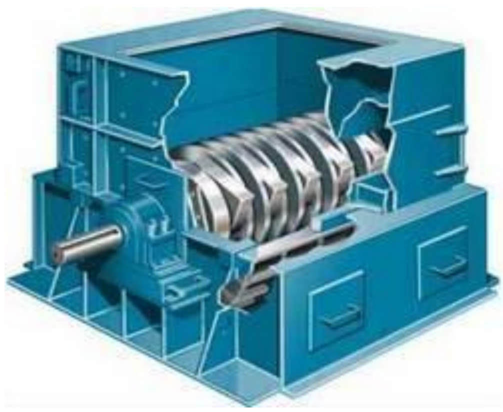


Figure 14. a) Disc and b) drum chippers [40], [42].

2.2.1.2. Jeffrey Rader Chip-Sizer

Jeffrey Rader Chip-Sizer is an innovative no-knife chipper, made to reduce oversized wood chips with a minimum of fines produced. Due to its high efficiency, extra screens are not required, reducing its maintenance cost. Its operating principal is similar to a wood hog, however, it operates at slower speeds–almost one third of the wood hog operating speed (Figure 15 and Table 8).

a)



b)

Figure 15. a) Jeffrey Rader wood chipper and b) zoomed view to the interior [43].

Table 8. Specifications of a typical wood-chipper (manufactured by Jeffrey Rader Corp.) [43].

Specifications	
Chip-Sizer model 56	
Max. feed capacity [TPH]	64
Chamber dimensions W x D x H [mm]	2,108 x 2,108 x 1,626
Estimated shipping weight [kg]	8,392
Operating speed [RPM]	400

2.2.2. Wood/bark hogs

2.2.2.1. General

Wood/bark hogs are reduction type of equipment that can handle a wide range of feedstock — wood and bark at paper/saw mills, wood yards etc. — under very surge conditions. The final product can be used as a feed-fuel in a power boiler (to a < 76.2 mm primary reduction size specification). Their main drawback is that they produce wood particles, with a less uniform size than actual “chip” specifications allow. The most well-known supplier is Jeffrey Rader company (Figure 16).

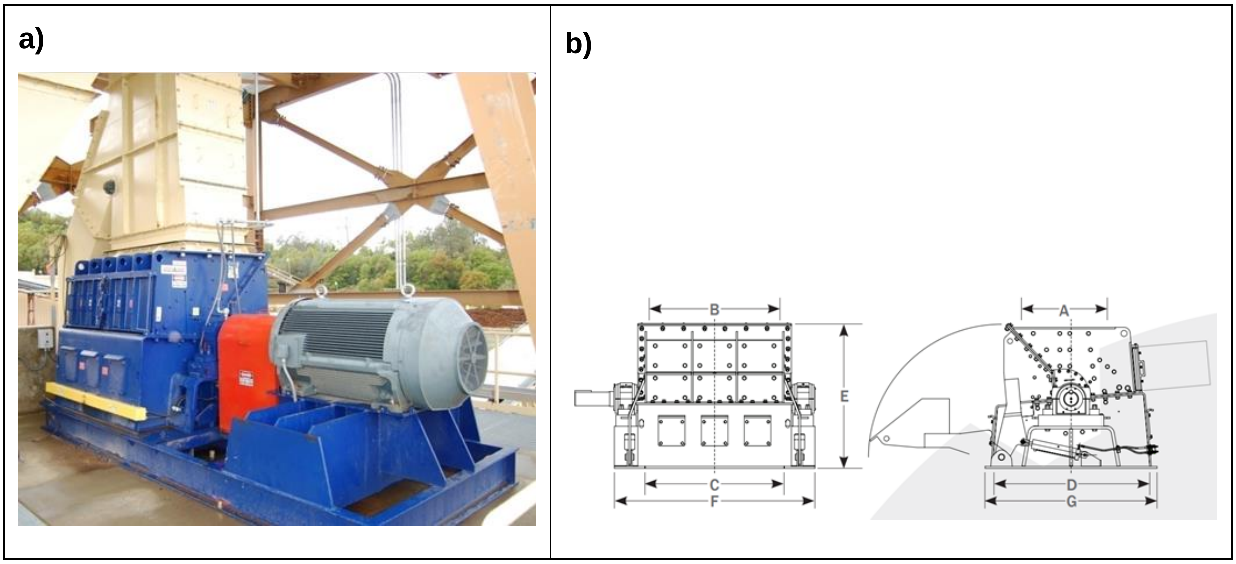


Figure 16. Jeffrey Rader wood/bark hog a) exterior view and b) schematic drawing [44].

Wood bark hogs can be non-reversible or reversible, with the latter having an increased wear life (Figure 17). The operation of a reversible hammer hog for size reduction of biomass — waste paper, fiberglass mats, or rubber — is more or less the same as the reversible hammer mill previously described. One major difference from the hammer mills utilized for sizing of coal or limestone is that in the case of biomass feedstock the machine should run at slow speed [45]. Additionally, the hammers are rigidly mounted on the rotating shaft or motor. On contrary, for pulverizing friable materials rectangular swing hammers are used.

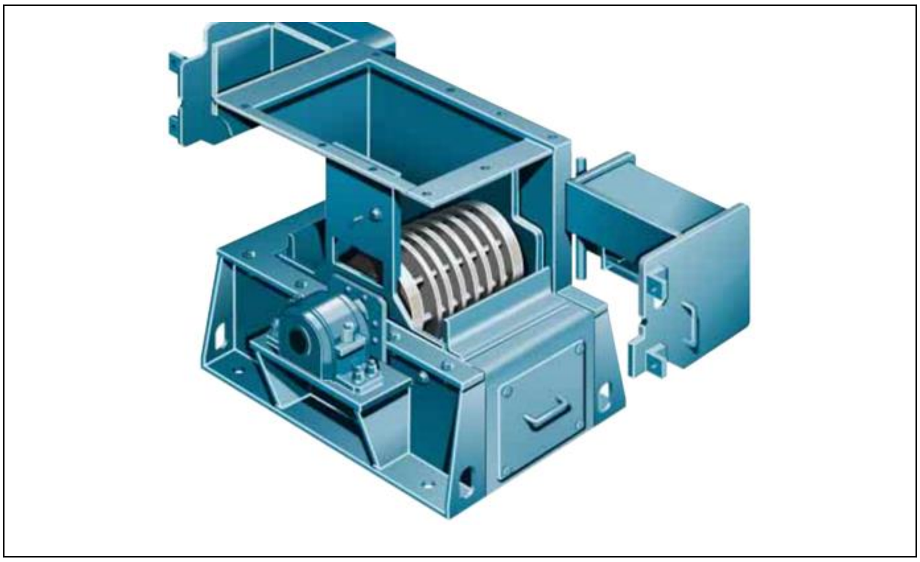


Figure 17. Jeffrey Rader reversible hammer hog [44].

In Table 9 are provided design characteristics for a wood hog that could be installed in industrial plant.

Table 9. Specifications of a typical Wood Hog (manufactured by Jeffrey Rader Corp.) [44].

Specifications	
55WBE EZ Access Wood Hog	
Feed-size [mm]	500 x 200 x 200
Final size [mm]	<100
Max. feed capacity [TPH]	30
Moisture [%]	50
Chamber dimensions W x D x H [mm]	1,600 x 2,184 x 1,829
Estimated shipping weight [kg]	7,500
Operating speed [RPM]	1,200
Horsepower [HP]	200-300

2.2.3. Chunkers

2.2.3.1. General

A chunker is a portable machine equipped with a spiral-head chipper (spiral-cutter blade mounted on a rotating shaft) or an involuted single-disk chipper (chipper blades mounted on the face of a thick steel disk) [46]. Chunkers are used for coarse (primary) biomass sizing, with a relatively low power consumption and number of fines. Chunk wood refers to short, thick pieces of wood of relatively uniform length of 50 to 250 mm. When the woody biomass is fed into the machine, it is drawn by the cutter and sliced into chunks (Figure 18).

a)

b)

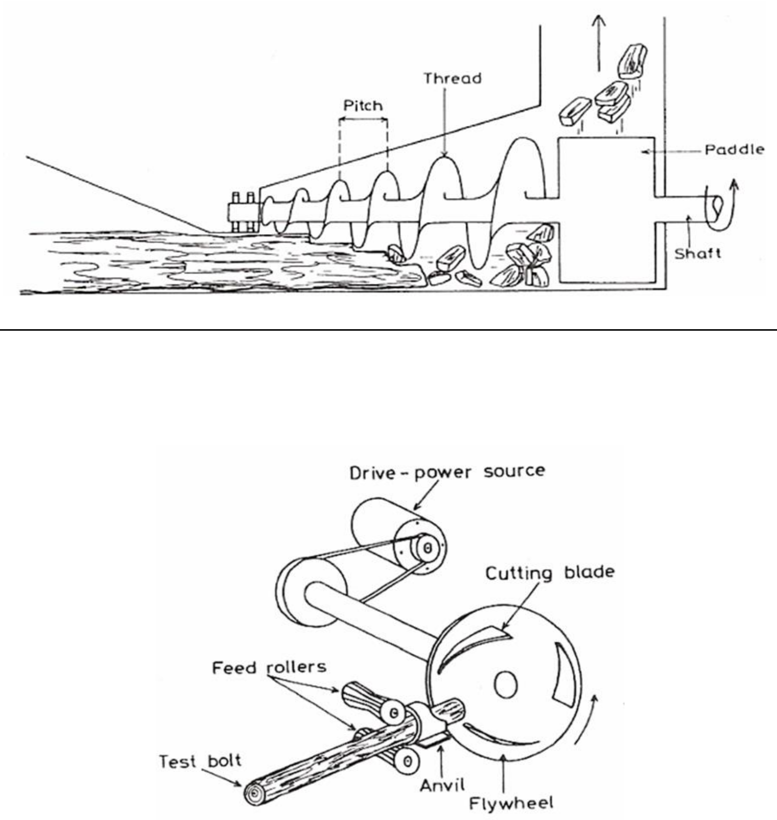


Figure 18. a) Spiral-head and b) Involuted single disk chunkers [47].

2.2.4. Straw Shredders

2.2.4.1. General

A straw shredder is a sizing machine for grinding large dry straw bales (500 to 700 kg) [48]. Bale shredders are generally used in organic fertilizer factories, cultivation factories and biomass fired plants. Straw passes through screens, in which the product size is determined. When material has been cut-off to the desired length, it falls onto a discharge conveyor (Figure 19). The higher the shredder operating speed, the higher would be its ability to produce shredded straw at a fast rate. However, higher speeds lead to a higher energy demand, which increases in turn the operating cost. In general, power requirements are high and losses of the fine material occur (from 5 % of up to 50 % depending on the bale feeding method employed).

When purchasing a straw shredder, it is important to look for one that has the least vibration and maximum efficiency while being safe and durable. It is also advisable to pick up a model, which can grind all type of straw. An automatic straw shredder would be the best choice because it does not require any supervising or monitoring. There are several European manufacturers for large round bale shredding systems that can serve all needs, such as Kverneland, Taarup, Teagle and Calvet [49]. Finally, reversible shredders are available in the market and provide all the advantages of unidirectional shredders along with lowest wear and, thus, maintenance cost and improved product size control due to the reversible rotor and adjustable breaker plates.

a) **b)**

Figure 19. Teagle bale shredder a) exterior and b) interior view [50].

In Table 10 are presented specifications of a typical bale shredder manufactured by Teagle.

Table 10. Specifications of a typical bale shredder (manufactured by Teagle) [50].

Specifications	
Tomahawk C12	
Final size [mm]	20-100
Max. feed capacity [TPH]	11
Max. moisture [%]	20
Max. grinding speed [bales/h]	25
Bale Chamber Diameter at Base [mm]	2,200
Estimated shipping weight [kg]	4,200
Operating speed [RPM]	500-1,000
Tractor horsepower [HP]	120-200

2.3. Costs of crushing equipment

Table 11 below shows a few approximate costs of the types of crushers presented in section 2. A comparison among them is challenging, due to the different fuel capacity ranges each type handles. Concerning biomass size reduction equipment, the knowledge is scarce. According to [43] [51], chippers require higher maintenance costs than no-knife chippers of wood hogs, since they are more sensitive to contaminants. However, wood chippers have lower operating cost per hour than wood hogs.

Table 11. Approximate averaged costs of typical crushers (data obtained from public data presented in websites of various manufacturers, as well as from quotations obtained from and discussions with them and with PPC) [11, 12] [30], [32], [35], [52], [53], [54], [55].

Model	Production ratio [TPH]	Capital cost (€)
Primary impactors	300	130,000.00
Secondary impactors	250	104,000.00
Tertiary impactors	250	52,300.00
Hammer mills	1.8	16,100.00
Reversible hammer mills	600	165, 000.00
Granulators	150	25,300.00
Double Stage Roll crushers	60	280,600.00
Single Stage Roll Crushers	200	133,000.00
Jaw crushers	200–500	98,550.00
Wood Hogs	30	79,300.00
Shredders	11	20,000-40,000

2.4. Summary

The final selection of the appropriate size reduction equipment is affected by different factors. The most important one is the material type (coal, limestone, biomass etc.) and its properties (hardness, moisture content, abrasiveness). Compression style crushers, such as a jaw crusher or roll crusher, are typically used with materials that are more abrasive. Impact style crushers, such as cage mills, hammer mills and impactors are used more for materials that are less abrasive.

The material type along with the combustion system that will be used determine in turn the desirable material final size, shape and crusher capacity. For instance, if the desirable material should have a cubical shape, an impact crusher must be used. However, in fluidized bed reactors the material does not play and an important role and, thus, a compression type crusher can be used, as well. Additionally, in fluidized beds the material can have larger size compared to PF boilers and thus, crushers of primary and secondary sizing can be used.

Cost — installation, maintenance and operating — is also an important factor, yet not the decisive one. For instance, roll crushers have the highest capital cost of all crushers. This is because they require very large rolls to achieve a reasonable reduction ratio of a specific feed. On the other hand, they are less sensitive to abrasive material, when compared to impactors or hammer mills. Thus, if abrasive coal or limestone is used in the process, then a higher maintenance cost will be required for an impactor (or hammer mill) compared to a compression type crusher, due to frequent replacement of blow bars, liners etc.

Similar to impactors, hammer mills, even though they have lower installation cost compared to other types of equipment used, they have high maintenance cost on abrasive materials and high operating cost, due to high power consumption; the power consumption is proportional to the reduction ratio and rotor speed. Finally, jaw crushers cost less to operate per unit, due to their low operating speeds (100–400 RPM) [56] and have a rather moderate maintenance and installation cost. Table 12 summarizes important characteristics of each coal/sorbent crusher presented above. These include relative maintenance cost, relative reduction ratio, use and grinding type.

Table 12. Characteristics of equipment for primary and secondary crushing [10], [57], [58].

Model	Relative maintenance cost	Relative reduction ratio	Use	Grinding type
Cage mills	High*	High (40:1)	Primary crushing, final sizing	Impact
Hammer mills	Moderate**	High (25:1)***	Primary crushing, final sizing	Impact, attrition, shear
Granulators	Low	High (10:1 up to 20:1)	Primary crushing, final sizing	Impact, compression
Double Stage Roll Crushers	Low****	Low (4:1)	Final sizing	Compression
Single Stage Roll Crushers	Low	Low moderate (6:1)	Final sizing	Compression
Impactors	High*****	High (35:1)	Final sizing	Impact
Jaw Crushers	Moderate	Low moderate (6:1)	Primary crushing	Compression

* Refers to traditional cage mills. It includes replacement of sleeves, bolts, bands, liners.

** Includes replacement of hammers, liners, screens or grate bars.

*** Refers to one-way hammer mills.

**** Refers to secondary crushing. When used for primary crushing the cost is higher.

***** Includes replacement of anvils and liners.

Taking the information presented through section 2 into account and following suggestions by PPC, compression type crushers must be used in a co-firing CFBC power plant for crushing the material. More specifically, for size reduction of coal, jaw crushers for primary crushing and single-roll crushers for secondary crushing are appropriate, whilst for limestone a double-roll crusher is recommended for use. Finally, for woody biomass size reduction wood hogs can be utilized.

3. Fuel feeding system

The reliable, safe and continuous supply of the fuel blend inside the furnace is the core of every power plant. The ideal feeder would have the following properties: high reliability, low construction, maintenance, and operational costs, low power consumption, wide applicability, smooth and continuous feed, suitability for handling a variety of bulk materials, insensitivity to variations in fuel quality, sufficient pressure seal against backstroke, accurate feed control, a construction suited to measuring the feed rate, durability, and availability. Commercial feeders are suitable for a narrow range of fuels [59].

Boiler fuel feed systems comprise storage, reclaim, conveying and feeding equipment (which are usually accomplished by the use of bucket elevators, fuel silos, gravimetric feeders, chain conveyors and screw feeders) [3]. This auxiliary equipment is used for fuel/sorbent discharge, storage, transport to the crushers and into the furnace. Crushed biomass is sometimes dried in air until the moisture content is less than 25% and then compressed into briquettes at a briquetting station before being sent to co-combustion [60]. Therefore, the types of equipment used for conveying various types of fuels must be chosen carefully to ensure proper operation.

3.1. Description of the feed lines

A typical fluidized bed boiler handling system typically includes [60]:

- Silos, hoppers and day bins
- Screws and chain conveyors
- Metering and robbing screw conveyors
- Feed chutes
- Rotary airlock feeders
- Gravimetric and volumetric feed controls
- Crushers, coal dryers etc.

Silos are typically cylindrical with a closed top and conical or mass-flow discharge bottom and are used to store large volumes of bulk materials at the beginning or the end of a process [61]. Hoppers are typically square or rectangular with an open top for loading purposes. Bins are square or rectangular and smaller in volume than hoppers; they are utilized for temporary storage of a solid material prior to its injection into the boiler and provide additional capacity to prevent from overfeeding. **Day bins** can be circular screw reclaimers in the bottom of silos, full live bottom screws, stokers or chains. After the day bins the solid material distribution to multiple feed points on the boiler can be accomplished by **conveyors**, **robbing screws** and **metering feed screws**. Nowadays, the fuel-feed systems are often equipped with proper fuel premixing and screening facilities [62].

The number of fuel feed points is important to evenly distribute the fuel into the boiler. It varies a lot among co-firing boilers and is dependent on the desired boiler capacity and fuel characteristics. The fuel normally enters the combustor through one or two feeders. A CFBC requires fewer feed points than BFBC does and is more tolerant to uneven fuel distribution and to larger fuel particles (0.25 to 2.5 in.), because of the high mixing rates and fluidization in the combustor [62].

One typical example of fuel-feed system structure is shown in Figure 20. Also, Figure 21 demonstrates the feeding of two separate fuels (coal and waste). The fuels are loaded from trucks into four silos. Feeding to the combustion chamber is divided into two independent lines, with each one of them having two silos. This is done so that one line can fulfil the fuel power needs in case feeding problems arise in the other line. Waste fuel and coal are mixed in **conveyors** before the fuel is fed through **rotary feeders** into the combustion chamber. The rate of fuel-feed is automatically controlled in response to the main steam header pressure [63]. It should be noted that coal, biomass, limestone, if used, and any other solid material should have a separate silo and silo discharger but the rest of the feeding system can be common for all solids [2].

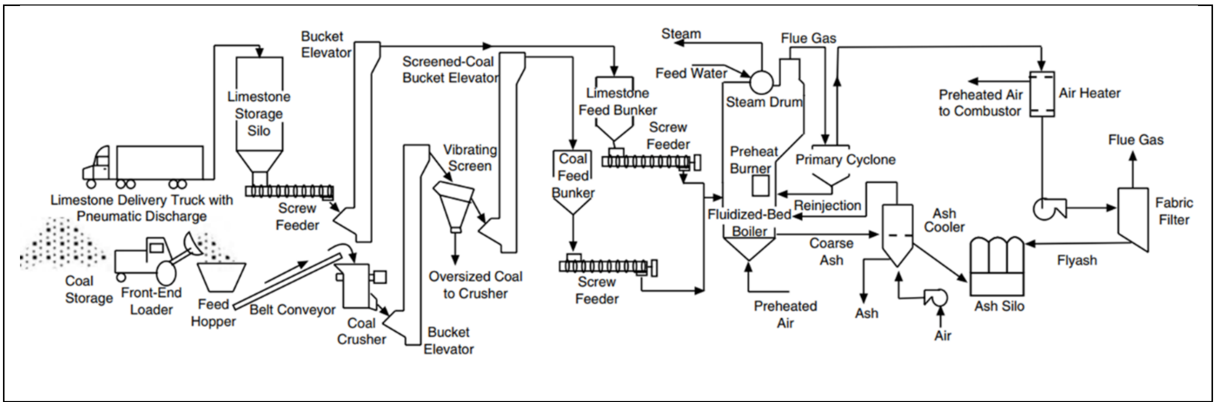


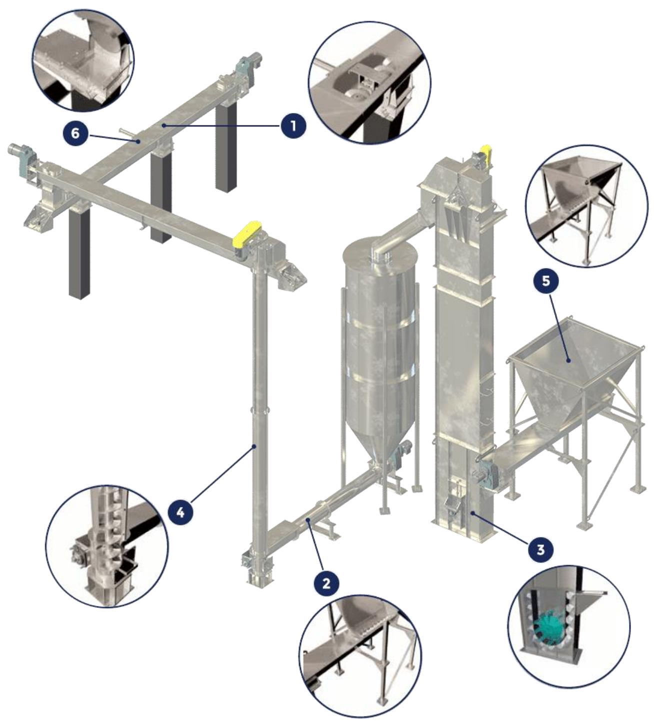
Figure 20. Arrangement of a typical fuel handling system [8].

Feeding systems are categorized in mechanical and pneumatic. Mechanical feeding is used when fuel firing in suspension is not required, whereas pneumatic systems can be used to inject fuels into cyclone, fluidized bed or pulverized coal type boilers or kilns.

i. Mechanical system brief description

In most cases of mechanical systems, **belt and screw conveyors** and bucket elevators are used for transporting coal, limestone or any other solid fuel across the different parts of the power plant. Initially, coal (lignite, hard coal, etc.), biomass and limestone arrive at the power plant by rail cars and/or trucks. Coal and biomass are conveyed by belt conveyors either directly to the crushers or to separate storage domes (silos). Additionally, bucket elevators are usually used for transporting limestone (or any other sorbent). Coal, biomass and limestone can by-pass the crushers if they are precrushed, pelletized or prepowdered, respectively. Another belt conveyor then carries the solid materials to day bins.

Both the fuel and limestone drop from the day bins into feeders through gravity **chutes** to control the flow to the boilers. The coal is metered by two **gravimetric belt feeders**, while the limestone is metered by two variable **speed screws**. The screws discharge into the outlets of the gravimetric feeders where coal, biomass and limestone mix and finally fall into the boiler. The limestone feed rate can be manually regulated for a predetermined fuel-to-limestone ratio, or automatically regulated based on a measurement of the sulfur dioxide in the flue gas. Each feed system consists of seal legs to prevent gas flow back through the feed system. Pulverizers are not needed in CFB systems; the fuel is coarsely crushed and fed to the CFB directly from the fuel silos via a simple gravity feed system. A typical fuel handling system proposed by KWS is depicted in Figure 21.



1. Screw conveyors
2. Screw feeders
3. Bucket elevators
4. Vertical screw conveyors
5. Hoppers, bins and silos
6. Slide gates

Figure 21. Arrangement of a typical mechanical system [64].

ii. Pneumatic system brief description

In pneumatic systems, the fuel (coal or biomass) is pneumatically conveyed by a positive pressure transport system to coal/biomass silo. Depending on its capacity, the silo can store enough fuel for some days. Coal/biomass feed in the boiler is handled by a pressurized gravimetric belt feeder that is controlled automatically based on steam demand. Limestone is delivered to the plant by pneumatic truck and is pneumatically conveyed to the silo. Limestone feed is monitored by a double helix screw feeder and is based on the coal feed rate. From the silos, the limestone is sent to a crusher and the coal is sent to a **crusher** and a **dryer**. Coal drying generally is not required for the boiler itself, but may be required for the solids handling equipment. Finally, the materials are pneumatically fed to the boiler.

In terms of feed points positions on the combustor in FBC processes, under bed and over-bed feeding can be used [65].

i. Under-bed pneumatic feeding

In the case of coal fuel, the particles crushed down to a size of 1–6 mm are pneumatically transported from a feed hopper (equipment also used for feeding reactors with operating pressure over 2.5 bar) to the combustor through a feed pipe piercing the distributor [59].

ii. Over-bed feeding

The 6–10 mm sized crushed coal is conveyed from a coal day bin to a spreader by a screw conveyor. The spreader distributes the coal over the surface of the bed uniformly. This type of fuel feeding system accepts over size fuel too and eliminates transport lines, when compared to under-bed feeding system.

A typical feed system for a CFBC would include a screw feeder or rotary valve to meter the fuel and sorbent flow (designs with a spreader are also being used). In rotary-valve feeders, the fuel is conveyed from an unpressurized space into a pressurized space in a pocket between the blades of the rotor and the frame of the feeder [59]. Coal drying is not regularly required for the boiler itself, but may be required for the solids handling equipment [62].

According to the system cases examined above, the diagram in Figure 22 summarizes the generic feed line applying to most of the solid boiler systems. Several companies worldwide can serve for an effective material handling in a CFB power plant [66, 67]. Screw Conveyor Companies for the energy industry in Europe and US are Kopar Oy and KWS, respectively. For refuse derived fuels, solid recovered fuels (RDF/SRF) and biomass handling BMH technology Oy is a commonly used supplier. Also, Jeffrey Rader supplies feed equipment facilities that are appropriate for feeding biomass and alternative fuels of high moisture content, including woody biomass, agricultural (straw) or RDF into boilers can be utilized [11, 12], [68].

According to the descriptions above, the most important components of a fuel handling system are silos, conveyors, crushers and dryers. Crushers have been analyzed in previous section and biomass/coal dryers have been reported in Deliverable 1.4. Therefore, the following sections will mainly focus on silos and conveyors.

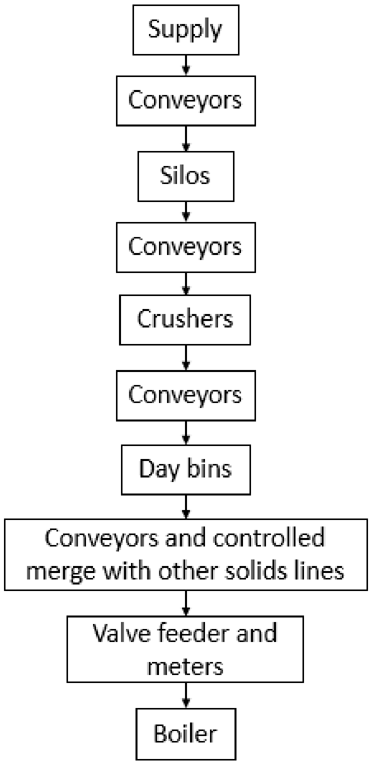


Figure 22. Generic illustration of feed process before combustion in fluidized beds for the solids supply.

Table 13. Suppliers of fuel handling equipment [11, 12], [26], [69], [70], [71], [72].

Company	Country	Bulk material	Handling equipment
BMH Technology	Finland	RDF, SRF, biomass	Screw/ drag chain conveyors, screw/ chain reclaimers, bucket elevators, shredder, crushers
Kopar Oy	Finland	Bottom and fly ash, chemicals	Storage and dosing systems, filtering and dust removal equipment, screening systems, silos and pressurized and non-pressurized tanks
Wamgroup	Italy	fly-ash, filler dust, silica fume, sand, limestone	Screw conveyors and bulk biomass conveying systems
Hapman	US, Canada	Calcium carbonate, pellets	Flexible screw conveyors, drag chain conveyors
KWS	US	Limestone, coal, biomass	Belt/screw conveyors, silos, hoppers, bins, bucket elevators
Jeffrey Rader	Global	wood chips, biomass, hog fuel, biomass, refuse derived fuels, coal	Screw conveyors, chain conveyors, silos, surge bins, metering bins and day bins, bucket elevators, rotary airlock feeders

3.2. Silos

Silos are facilities that are used for the fuel and sorbent storage, keeping, thus, the power plant running with a constant flow of materials. More specifically, they can be used to store grain, coal, cement, carbon black, woodchips, food products and sawdust. A complete set of coal silo would include a feeding system (conveyor), a dedusting system (in the case of coal silo), a gas path arch breaking device, the silo body, an electrical control system and other auxiliary equipment [73]. Fuel should be tested for bridging and flowability characteristics to determine a suitable silo shape. It is recommended they have a live bottom reclaim such as screw conveyors (3.3.3). Jeffrey Rader silos (Figure 23a) are appropriate for wood chips, bark, hog fuel, biomass and RDF products storage before being used in the boiler. Other suppliers of steel or aluminum silos are Conair (Figure 23b) and Skandia Elevator [74].

Regarding coal storage, cement silo and silo constructed of bolted metal panels (usually steel or aluminum) are usually used in power plant installations. The most commonly used are the Lipp silos [75] type of the steel silos group. This is because steel silos require a short construction period, they have a long service life and good sealing performance. It is reported that Lipp silos are more economical and practical than cement silos.

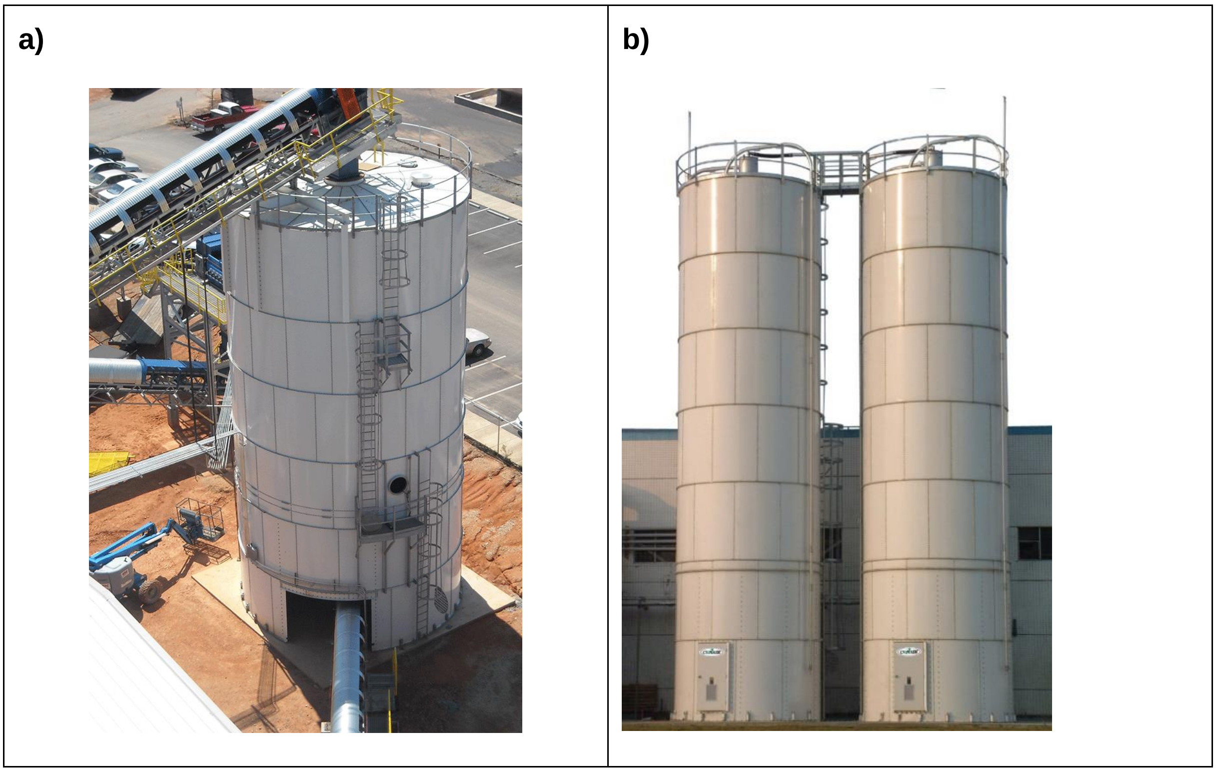


Figure 23. a) Jeffrey Rader grain silo [11, 12] [76], b) Conair coal silo [74]

3.3. Conveyors

3.3.1. Introduction

Fluidized bed based thermal power plants rely on conveyor transport systems to transport coal, biomass and limestone from the unloading point to the storage site (silos) and from the storage site to the furnace. The type and number of transport systems is highly dependent upon the power plant site and more importantly on the load capacity and type of fuel blend. For feeding fuel and sorbents, such as limestone or dolomite, different methods are used, depending on the type of the fluidized bed reactor.

There are several types of conveyors in the market, some of which are: belt conveyors, plate conveyors, pipe conveyors, screw conveyors, submerged chain conveyors and roller conveyors. The major types of mechanical conveyors used in the fluidized bed technology are the belt and screw conveyors. Other common types are the chain-type conveyors, sweeps and bucket elevators [77].

3.3.2. Belt conveyor

Belt conveyors (or band conveyors) are used to transport large volumes of any bulk material and unit loads (50–100 TPH) — both horizontally and sloping — over long distances (up to 400 m) [78]. Depending on inlet point and method of use, belt conveyors can be used as fixed or mobile systems. In a belt conveyor, the one-piece belt is both the transport and the drive mechanism as it is carried by support rollers (or idlers) or a sliding table. This belt is usually made of rubber, balata or canvas and runs over pulleys or a pair of drums. Distance among support rollers, belt quality, tensioning, and other characteristics depends on inlet position and material specifications (capacity, weight etc.) [78, 79].

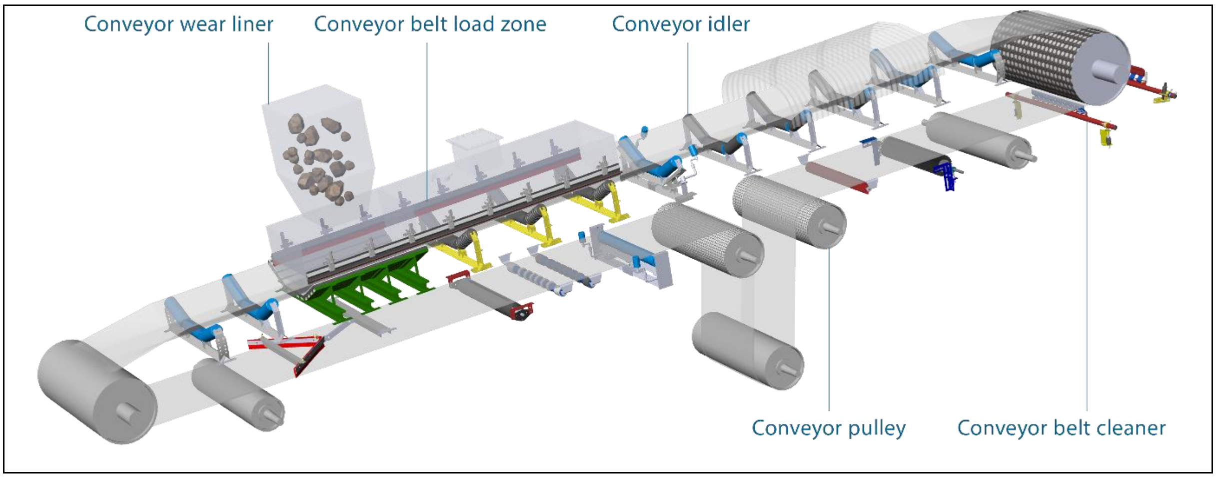


Figure 24. Belt conveyor arrangement [80].

Transport speed is calculated based on transport capacity and inlet points, and will utilize either a flat or a troughed station with a suitable support roller diameter. Flat and profiled belts are anti-static, abrasive-resistant and can be delivered in a variety of grades. Depending on the size of the radius, belt conveyors can be driven on a horizontal, concave or convex path. A reverse mode is also possible.

The main advantage of belt conveyors is that they offer a low power consumption and a highly economical transport method that requires minimum repair and maintenance. They also allow for easy protection of the load from wind and rain with over-head covers. Table 14 presents specifications of belt conveyors manufactured by Skandia Elevator [81].

Table 14. Typical belt conveyor specifications [82].

Belt conveyor (BTI)	Units	BTI 400	BTI 500	BTI 650
Capacity*	TPH	66	100	150
Nominal drive shaft	RPM	194–209	194–209	161–178
Belt speed	$m \cdot s^{-1}$	2.4	2.4	1.96
Belt width	m	0.4	0.5	0.65
Length**	m	10	10	10

* at 750 $kg \cdot m^{-3}$

**max length 100 m

3.3.3. Screw conveyor

Screw conveyors are used for transporting powdery, granular and wood-based materials. They are cost-efficient solutions for conveying materials over short distances, when they are compared with belt conveyors. A screw conveyor contains five basic elements, i.e. frame, screw, bearing housing and sealing, operating unit and hatches. Depending on their arrangement they can be categorized into vertical, horizontal (Figure 25), and inclined screw conveyors [59, 83], [84].

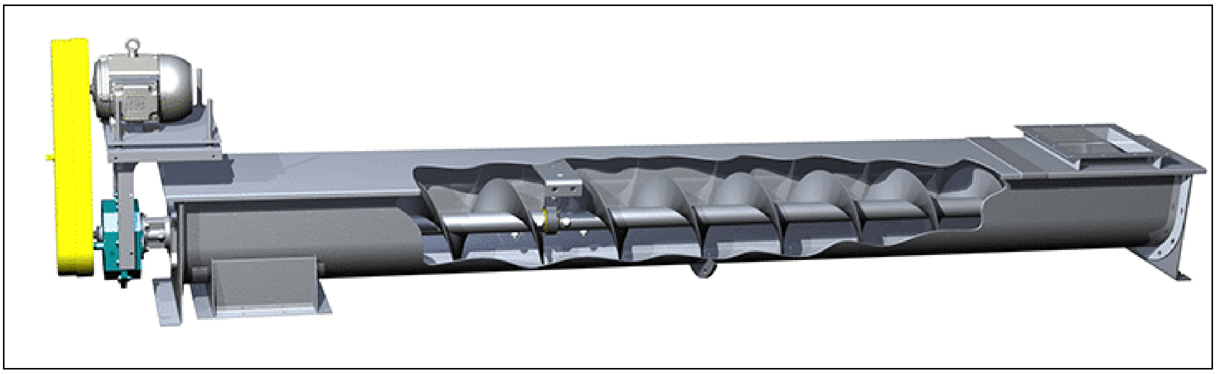


Figure 25. Typical horizontal screw conveyor manufactured by KWS [64].

More specifically, screw conveyor frames can be U-trough, rectangular-trough or tubular (Figure 26). Frames and screws can be manufactured of carbon steel, acid resistant steel, hot-dipped galvanized or stainless steel. Connections to other equipment or processes are also built of the same material.

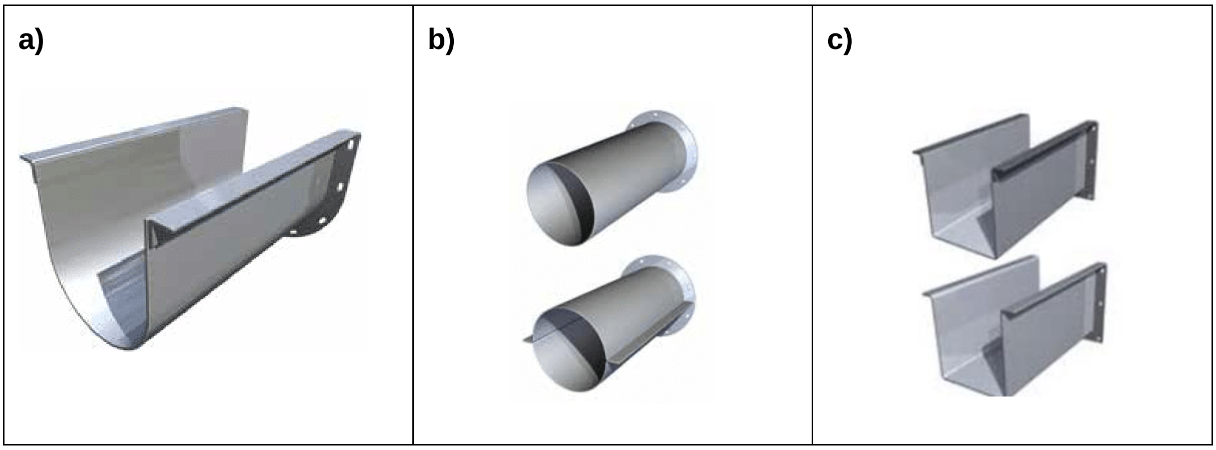


Figure 26. a) U-trough, b) tubular and c) rectangular screw conveyors [85].

Depending on the transport capacity, screws can have a diameter of 150 to 500 mm, and a speed varying from 70 to 120 RPM. However, much attention should be paid on the screw speed and loading, especially when a granular material is to be transported, in order to avoid to reduce the chance of fluidizing the material. More specifically, a screw conveyor should be designed with very low speed and trough loading, typically 15-percent or less and with a screw of shorter pitch that decreases the distance between flights. The short pitch flighting will slow material flow through the conveyor [86].

Screw conveyors come with an affordable initial cost, and offer the simplest and most compact transport method. They also have provisions that allow you to dust proof your coal during the transportation. Screw conveyors wear and tear fast, and consume more power per transport while compared to belt conveyors. The torsional strain of the shaft also limits the length of the feed; it cannot exceed 30 m.

Following the above analysis, it is deduced that when selecting a screw conveyor for a fluidized bed boiler application there are several aspects that should be taken into account [83]:

1. Bulk material type, condition (maximum particle size and specific bulk density) and feed rate of capacity
2. Required distance and incline of the bulk material to be conveyed (vertical, horizontal etc.)

3. Design parameters (materials of construction, inlet feed conditions and operating temperature)

Table 15. Typical design parameters of screw conveyors [87].

Screw conveyor	Units	Type 1	Type 2
Capacity	TPH	30	50
Pipe Diameter	m	0.2	0.25
Length	m	6	10
Type	-	Tubular	Tubular

3.3.4. Chain conveyor

Chain conveyors (or drags, scrapers, paddles) are conveyance type machines that start out with a continuous chain and fixed flights operating within an enclosed trough [88]. They are suitable for transporting grain and most dry granulated and pulverized materials over long distances. They are widely used in heavy-duty industries and power plants, because of their low maintenance cost, low motor power requirements and high usage of their conveying space, compared to other types of conveyors. For instance, a typical belt conveyor uses 20–25% of available conveying space to move bulk material, whilst a typical drag or paddle conveyor uses 45–50% of available conveying space [88]. As a result, the overall size of drag conveyors is smaller when compared to other conveying systems and technologies moving the same volume [69]. On the other hand, there is some risk of degradation of the conveyed material, whilst their installation cost is higher compared to belt or screw conveyors.

Chain conveyors can be used as both bottom and top conveyors and are available in models that are capable of working with 0º, 15°, 30° and 45° inclinations. A bottom conveyor can be used to transport material from storage bins/silos or other bottom conveyor to a belt & bucket elevator. When feeding from a storage bin/silo a raised inlet is used that is self-regulating, which prevents overfilling. Bottom conveyors are usually horizontal or curved. On the other hand, top conveyors can be fed by a bucket elevator and can be horizontal, curved or inclined. Another type of chain conveyor available in the market is the trench intake conveyor, which is usually used to convey material from a trench intake (such as from a silo or day bin) to a bucket elevator [89]. All these types of chain conveyors are depicted in Figure 27. Table 16 presents a comparison of characteristics among different types of chain conveyors that can be installed in a power plant. A conclusion to be drawn is that chain conveyors are more expensive than screw conveyors. Additionally, an inclined or curved conveyor is usually more expensive than a horizontal one with the same design specifications, Table 16.

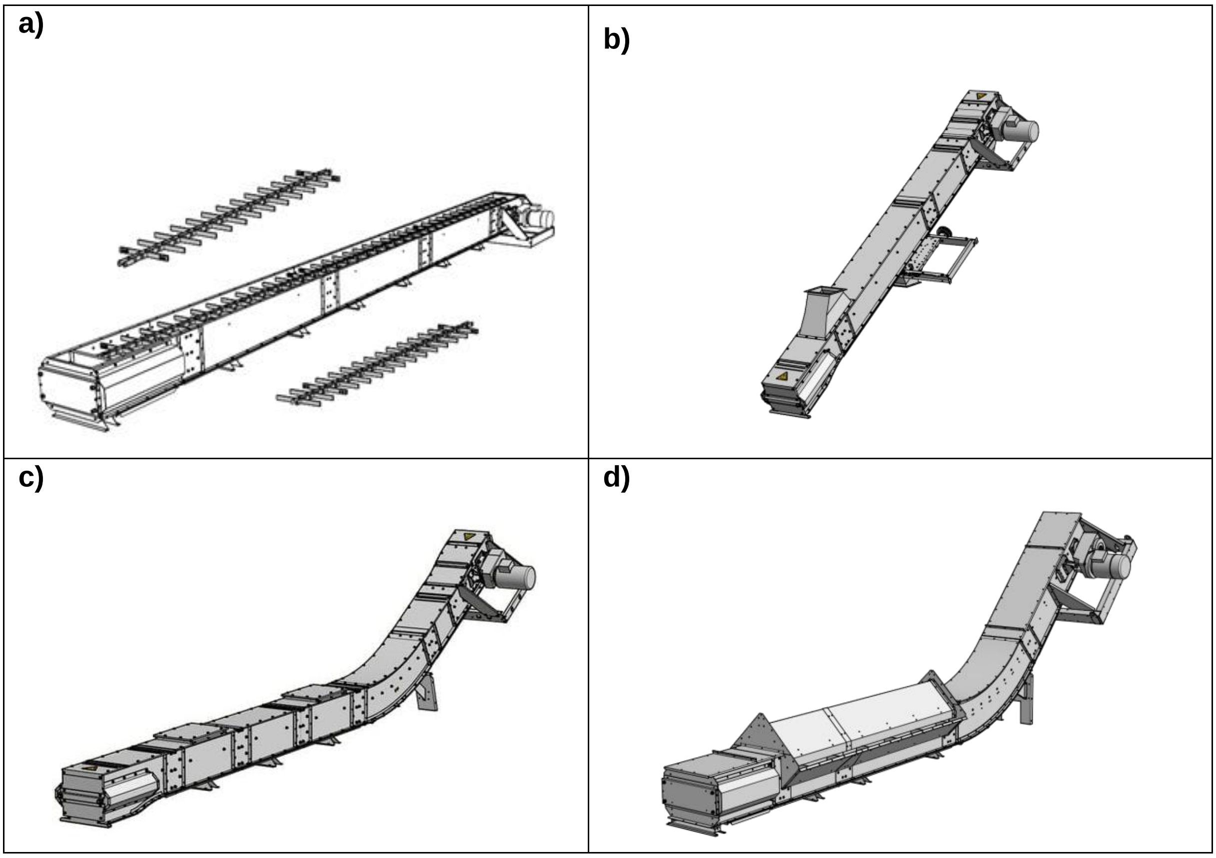


Figure 27. Drag chain a) horizontal [90], b) inclined, c) curved and d) trench intake conveyor [90] [81].

Table 16. Specifications comparison among different types of chain conveyors [91].

Chain conveyor	Units	KTHb 20/33	KTHb 30/33	KTH 20/33	KTH 30/33	KTHA 20/33	KTHA 30/33
Capacity (for 760 kg·m^{-3})	TPH	56–60	97	68	113	66	113
Dimensions W x H	m	0.2x0.335	0.3x0.335	0.2x0.335	0.3x0.335	0.2x0.335	0.3x0.335
Length	m	10	10	10	10	10	10
Speed	RPM	44	49	44	49	65	56
Chain speed	m·s^{-1}	0.59	0.65	0.59	0.65	0.87	0.75
Conveyor type	-	Bottom horizontal	Bottom horizontal	Top horizontal	Top horizontal	Top Inclined	Top inclined

3.3.5. Sweep conveyor

A sweep conveyor is used for emptying a silo/bin and transport a bulk material into a bottom conveyor, by leaving only a small amount of grain inside the silo (Figure 28 and Table 17). It can be operated without being exposed and moves safe and steady without slipping.

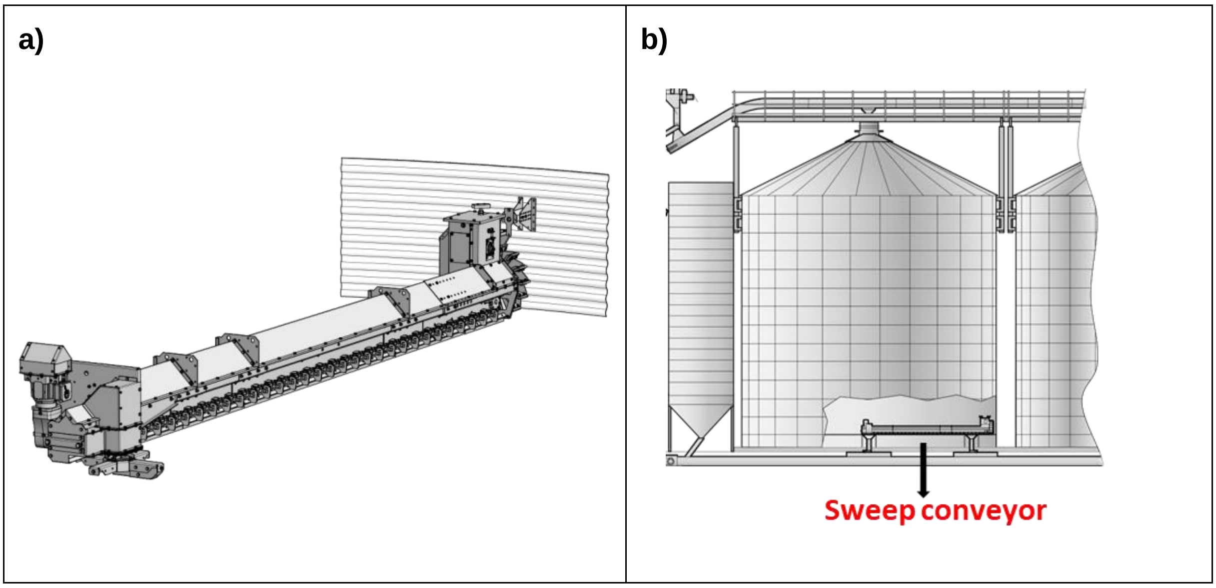


Figure 28. Sweep conveyor a) design and b) arrangement inside a silo [92].

Table 17. Sweep conveyors specifications [92].

Sweep conveyor	Units	KTIS 15/25	KTIS 15/25
Capacity (for 760 kg·m^{-3})	TPH	55	55
Length (Max)	m	12	12
Speed	RPM	154	154
Chain speed	m·s^{-1}	0.96	0.96
Silo height (Max)	m	25	25
Silo diameter (Inner, Min)	m	6.5	10

3.3.6. Bucket elevator

Bucket elevators are the simplest units for making vertical lifts. They contain a series of buckets attached to a chain or a belt that moves over pulleys or sprockets located at the top and bottom of the unit. The buckets carry the bulk material (fuel, sorbent, sand) at the bottom and discharge it at the top. They are available in a wide range of capacities from different suppliers and can operate entirely in the open to all kinds of weather conditions for many years or be totally enclosed [10]. The bucket elevator conveyor limits transports to 30 meters vertically, with a maximum horizontal inclination of up to 60 degrees. Skandia Elevator elevators found in the literature are used in many applications, because they can handle capacities up to 600 TPH (Figure 29). They are made of galvanized steel and are compliant with the EU's Machinery Directive [91]. Besides grain, they can transport most dry granulated (of maximum moisture content equal to 15 %) and pulverized materials. It should be noted that every 1% increase in moisture content above 15%, decreases capacity by 3–4% [91].

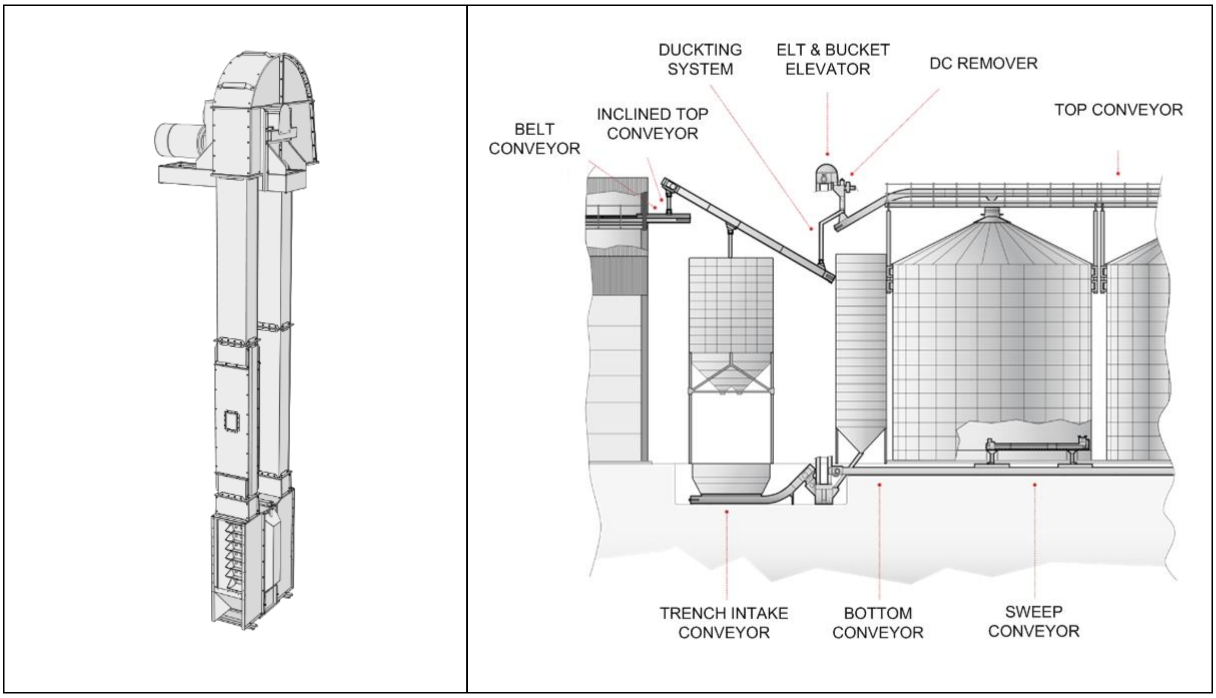


Figure 29. Belt and bucket elevator a) design and b) arrangement in a feeding system [91].

3.4. Costs of fuel feeding systems

Table 18 below shows a few approximate costs of the types of feeders presented in section 3. A comparison among them is challenging, due to the different fuel capacity ranges each type handles. Cost of coal silos from European companies could not be easily found, however such data can be considered as indicative for a cost analysis.

Table 18. Approximate averaged costs of typical feeders (data obtained from public data presented in websites of various manufacturers, as well as from quotations obtained from and discussions with them and with PPC) [73], [82], [87], [91], [92], [78], [91], [93].

Model	Production	Capital cost (euro)	Operating cost / Maintenance
Lipp silos	3,200 m^3	185,200.00	Long service life, good sealing performance.
Concrete silos	3,200 m^3	244,700.00	Shorter service life than Lipp silos
Belt conveyors	70–150 [TPH] (at 750 $kg \cdot m^{-3}$)	1,200.00 (motor) + 8,000.00 (conveyor)	Low power consumption, minimum repair and maintenance
Screw conveyors	30–50 [TPH]	2,000.00–4,000.00	Power consumption per unit weight transported is considerably high. High wear and tear and shorter life compared to belt conveyors.
Chain conveyors	60–110 [TPH] Capacity (for 760 $kg \cdot m^{-3}$)	1,400.00–2,900.00 (gearbox) + 6,900.00–11,700.00 (conveyor)	Significant energy savings due to low energy consumption
Sweep conveyors	55 [TPH] Capacity (for 760 $kg \cdot m^{-3}$)	1,100.00 (gearbox) + 6,000.00 (conveyor)	Minor energy requirements
Bucket elevators	60–100 [TPH]	7,000–18,000	Similar energy requirements to belt conveyors for given unit weight and height difference

Each piece of conveying equipment is unique, and each manufacturer has its own set of rules by which to maintain the equipment. It would be difficult to include specifics of maintenance requirements on each make and model used in the industry, due to the different rules set by the different manufacturers. A few general practices and procedures include the checks for spills (leaking), sounds, weather tightness, rust or corrosion [94].

Table 19 below demonstrates indicative pricing for a fuel handling process equipment in a lignite plant of approximately 100 MW. Data are supplied by PPC. It is to be noted that these data refer to a pulverized fuel power plant, thus some parts of handling system (e.g., pulverized lignite ducts etc.) are likely to be omitted in a CFB combustor.

Table 19. Lignite conveying system pricing list (prices indicated by PPC).

	Equipment	Equipment price (at site) (€)	Installation price (€)
Conveying system before crusher (raw lignite)	Raw lignite transportation belt conveying system	399,500.00	55,900.00
	Housed conveyor bridge of raw lignite transportation belt conveying system	374,500.00	52,300.00
	Equipment of the side bin (vibration feeder, traveling & reversible belt conveyor, metal detectors)	31,200.00	4,300.00
Crushed lignite conveying system	Crusher discharge travelling belt conveyor	162,300.00	22,700.00
	Crushed lignite transportation belt conveying system	249,700.00	34,900.00
	Housed conveyor bridge of crushed lignite transportation belt conveying system	163,000.00	22,800.00
	Travelling and reversible belt conveyors for lignite discharge to the boiler silos	187,200.00	26,200.00
	Metal detectors and metal removing systems	349,500.00	48,900.00
	Lignite sampling system	249,700.00	34,900.00
	Lignite weighing system	499,300.00	69,800.00
Lignite feeding system to boiler	Day bins (bunkers) connecting frame shut-off devices and lignite extractors	1,162,400.00	122,000.00
	Lignite feeders including driving units (motor gears, couplings, plate conveyors, steel structure etc.)	255,600.00	26,800.00
	Pulverized lignite ducts	188,500.00	19,800.00

3.5. Summary

This section first described the required equipment for fuel feed lines in solid fuel power plants, and then focused on the most important components of it that have not been already examined; the silos and conveyors. Boiler fuel feed systems include storage, reclaim, conveying and feeding equipment to store, transport and discharge fuel/sorbent to the crushers and into the furnace. The fuel normally enters the combustor through one or two feeders to evenly distribute the fuel. Feeding is divided into two independent lines, so that one line can fulfil the fuel power needs in case feeding problems arise in the other line. Distribution conveyors, robbing screws and metering feed screws facilitate distribution to multiple feed points.

Feeding systems are categorized in mechanical and pneumatic, the first being used when fuel firing in suspension is not required, whereas the second being used for injection of fuels into cyclone, fluidized bed or pulverized coal type boilers or kilns. In terms of feed points positions on the combustor in FBC processes, under bed and over-bed feeding can be used. In under-bed feeding, smaller size particles are pneumatically transported to the combustor, whereas in over-bed feeding larger coal particles are conveyed from a coal day bin to a spreader by a screw conveyor.

Silos are facilities that are used for the fuel and sorbent storage, keeping, thus, the power plant running with a constant flow of materials. The main types used are the Lipp silos, other steel silos and cement silos. Day bins stores bulk temporarily to control overfeed. The main types of mechanical conveyors examined are the belt, screw, chain-type conveyors and sweep conveyors, as well as the bucket elevators. In addition to the conveyors, the feeding systems of the fluidized beds are typically equipped with fuel pre-mixing, screening and auxiliary facilities as well (such as rotary-valve feeders). The number and position of feed points depend on the combustor capacity and determine distribution of the fuel in the chamber. A comparison among them is challenging, due to the different fuel capacity ranges each type handles.

A typical fuel-feed system structure in the case of feeding of multiple fuels (coal and biomass) and sorbent would include the following components: conveyors to move particles from the supply trucks to silos, followed by other conveying equipment to facilitate transport to the crushers, then conveyors to transport to the day bins, and, lastly, conveyors, valve feeders, meters and flow controllers that merge the various solids and insert them into the boiler. Coal, biomass, sorbent, and any other solid material should have a separate silo and silo discharger but the rest of the feeding system can be common for all solids. Several companies worldwide capable of material handling in a CFB power plants include Kopar Oy, KWS, BMH technology, Jeffrey Rader and Skandia.

The types of silos and conveyors used in power plants were compared in terms of the suitability for handling a variety of bulk materials, their applicability, particles size reduction range, dimensions and distances of transportation. Costs of the different silo and conveyor types were compared, while their aspects related to operation and maintenance were mentioned, as the ideal feeder would need high reliability, low construction, maintenance, and operational costs, low power consumption.

Belt conveyors are suitable for conveying abrasive, sticky or corrosive material, with high loads. Screw conveyors usually transport powdery, granular and wood-based materials at lower loads. Chain conveyors transport grain and most dry granulated and pulverized materials, either from the top or the bottom of the boilers, occupying smaller size for the same mass handled when compared to the other conveyor types. Sweep conveyors transport bulk material into a bottom conveyor. Bucket elevators move most dry and granulated materials and are available in a wide range of capacities.

The distances that can be covered by the different conveyor types are long for the belt and chain conveyors, while they cannot exceed 30 m length in the case of screw conveyors and bucket elevators. In terms of inclination, belt and chain conveyors can have horizontal or any inclined position, while screw can be vertical too, and bucket elevators are mostly vertical with small inclinations. The rotation speed of the different conveyor types varies, with belt conveyors having the highest speeds, followed by sweep, and the rest of the conveyor types.

Regarding capital costs, Lipp silos are more economical and with longer service life than concrete silos, belt and screw conveyors are economical, while chain conveyors have high installation cost and the screw conveyors have high cost per volume handled. Regarding maintenance of the conveyors, belt conveyors require minimum repair and maintenance than chain conveyors and have minor power consumption, making them the most economical method. They also have easy protection of the load from extreme weather conditions. Screw conveyors have considerably higher power consumption per unit weight transported, and while they allow to dust proof fuel, their wear and tear is very fast and therefore their lifetime is relatively shorter. Chain conveyors have low maintenance cost, low motor power requirements, but have high risk of degradation of the conveyed material. Bucket elevators can operate at all kinds of weather conditions for long time. Lipp silos and belt conveyors are combining most of the advantages from the examined characteristics for storage and feeding equipment, respectively. Belt conveyors were used by the lignite conveying system of PPC used for the pricing list analysis shown in Table 19.

4. Conclusions

A thorough investigation has been conducted in the framework of Task 1.2 to identify the current state-of-the-art crushing and feeding systems able to be utilized in industrial scale fluidized bed reactors. Various industrially operating crushing systems that are used for coal fuels beneficiation for CFBs have been presented, including different types of cage mills, of impactors, of hammer mills, granulators as well as roll and jaw crushers. Biomass particles size reduction systems, including wood chipper, hogs and chunkers, and straw bale shredders have been described too, as the project examines co-firing scenarios in CFBs. Their systems characteristics have been presented and compared, in terms of their capacity, operating conditions, handled particles, size reduction ability, energy requirements, particle top-size and final size, production ratio, dimensions, as well as prices.

Based on an extended literature survey and contact with manufacturers it is concluded that in a co-firing CFBC plant, compression type crushers must be used for crushing coal and the sorbent material. Such crushers have the highest installation costs compared to the rest of the crushers found in the market, however, they seem to be the most cost-effective in terms of maintenance and installation cost. Therefore, a compression type double-roll crusher should be used for size reduction of limestone and a single roll-crusher for crushing of coal. If coal is oversized, when arriving at the plant, then a jaw crusher can be used for primary crushing prior to the double-roll crusher. Finally, wood hogs and bale shredders can be utilized for size reduction of woody biomass and straw bales, respectively. It should be underlined that the above conclusions depend on the initial and final (desired) size of the particles and their properties. However, the above conclusions are true for the majority of cases.

Apart from crushing equipment storage and feeding systems have also been investigated; design principles and characteristics of silos and conveyor types (i.e. belt, screw, chain, sweep, bucket elevators) have been presented. Lastly, data obtained by the PPC regarding costs of a lignite feeding system have been obtained for the purpose of an approximate estimation of the system requirements. Lipp silos and belt conveyors are combining most of the advantages from the examined characteristics for storage and feeding equipment, respectively.

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