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Influence of physical properties of solid biomass fuels on the design and cost of storage installations

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ABSTRACT

The aim of this work consists on determining biomass fuels properties and studying their relation with fixed and variable costs of stores and handling systems. To do that, dimensions (length and diameter), bulk density, particle density and durability of several brands and batches of wood pellets and briquettes were tested, according to international standards. Obtained results were compared with those in literature. Bulk density tests were applied for several other biomass fuels too, and later used to determinate which ones of all the biomass-fuels tested are economically more profitable for a typical transport/store system made of a screw conveyor and a concrete bunker silo.

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1. Introduction

Recent decades have witnessed the emergence of new energy policies worldwide aiming to ease global warming. These are based on environmental sustainability, competitiveness and safety of the energy supply (Hoffmann et al., 2010). Because of this, renewable energy sources, like biomass, are a pillar to achieve a sustainable energetic model (Gaska and Wandrasz, 2008). Biomass is substantially available everywhere, whereas major fossil fuel reserves are concentrated in a small number of countries. Furthermore, it is CO₂-neutral when used in combustion (García Fernández et al., 2012). Biomass encompasses wood, industrial and forest wastes, energy crops, cereals and municipal solid wastes (MSWs), that includes municipal solid biomass (MSB) (Šulc et al., 2012).

The European framework for energy calls for the use of biomass in electricity, heat and transport, to reach 20% of all energy use from renewable sources by 2020. To achieve this, biomass fuels must reach quality standards, since logistic operations and side costs seem to constitute a huge bottleneck in the biomass use development. In this way, waste biomass supply chains (WBSCs) consist of four different steps: biomass harvesting and pre-treatment, storage, transport and energy conversion (Iakovou et al., 2010) (Fig. 1).

Usually raw biomass present high moisture content, irregular shapes and sizes and low bulk density, meaning low energy density and making it expensive and difficult to manage. Pellets making by

densification increase the bulk density from 40 to 250 kg/m³ of straw or raw wood to 600–800 kg/m³ (Kaliyan and Morey, 2009; Mani et al., 2003). It also decreases the moisture content increases product homogeneity and reduces transport costs and residues, improving wood wastes marketability (Carone et al., 2011). To optimize this process, both raw biomass properties and process parameters have deeply been studied (Relova et al., 2009). As wood wastes physical properties are influential in the installation design, an in depth physical characterization is highly recommended. The aim of this work is to relate these wood wastes properties with storage (silos and bunkers) and handling equipment and determine to what extent differences in the former influence the latter.

Major physical parameters to evaluate densified biomass are size and shape, bulk and particle density and durability (Gil et al., 2010; Lu et al., 2010). Some of these can be determined using some of the international standards shown in Table 1:

1.1. Physical properties of biomass pellets

- **Size and shape**, are related with moisture content, and measured using a gauge.
- **Bulk density** affects the combustion efficiency of the fuel, and depends on physical characteristics of the raw wood (Theerarat-tananoona et al., 2011).
- **Particle density** is defined as a sample's mass/volume ratio. Higher density means higher compression and energy density (Mani et al., 2006), but not higher durability (Oberberger and Thek, 2004). The volume can be approximated by using liquid displacing, stereometric or solid displacing methods (Temmer-

Fig. 1. Waste biomass supply chain (WBSC).

man et al., 2006). If sample is irregular, its volume is approximated to a regular figure's one. All these methods were reviewed in depth and their results compared by Rabier et al. (2006). Other options to obtain the particle's volume are by using a 3D image processing algorithm (Igathinathane et al., 2009) or by using a helium displacement pycnometer (Miao et al., 2011). Among all the available methods to develop these experiments, some widely reported and simple ones were selected for this work.

- As defined by Carone et al. (2011) **durability** represents the ability of densified fuels to remain intact during handling and **delivery**. It plays a key role during transport and storage. Poor durability values lead to dust emissions, entailing health problems, non-homogeneous combustions and explosive-atmosphere risks (Temmerman et al., 2006). It depends on the physical properties of the wood, process and densification equipment used (Fasina, 2008). It can be measured by using several methods such as the tumbling can method, comprehensively described at ASAE 269.4 standard (Serrano et al., 2011). The Holmen method (Kaliyan and Morey, 2009) or the Ligno-tester method (Oberberger and Thek, 2004) which is the one recommended by ÖNORM M 7135 standard. Mabrik tester device is described by Serrano et al. (2011). Temmerman's and Kaliyan's makes an in depth review of most of these methods. Kaliyan also proposes an impact resistance method (Kaliyan and Morey, 2009). There is no standard criteria for durability acceptance levels, but different options proposed in the literature are gathered by Kaliyan and Morey (2009). In this way, Adapa classified alfalfa pellets' durability as either high (over 80%), medium (between 70% and 80%) or low (below 70%). Waelti and Dobbie classified straw cubic pellets' durability as "good" (between 80% and 90%) or as "very good" (over 90%). Richards (1990) established a durability acceptance criterion for coal briquettes at 95%. Finally, ASAE standards determines that using Ligno-Tester durability must be over 97.7%.

1.2. Storage and handling of biomass pellets

- Storage** is required to assure fail-safe process as "just in time" (production of required elements, in required quantities in the moment they are required) is not always possible. Store design

implies location, type, shape and size of a facility. An store can be **located** in or out of a building depending on the size, available space or kind of solid. There are many structures available in the market, generic or designed for specific uses, depending on the **type, shape and size**. Selection depends on the fuel, structural characteristics or weather severity (Nogués et al., 2010). Some options are **silos and hoppers**, **flexible silos** or **textile-made big bags**, which are normally used for pellets; or buried **bunkers**, also called **civil work silos**, that are the most common nowadays. Other possibilities are low-capacity **air pumped silos** or **sloped silos**. In most type of stores densified wood or any other fuel must be unloaded by gravity, whilst in bunkers it must be complemented with mechanical systems, such as pushing hydraulic systems (moving floor) and screw conveyors (Pizarro et al., 2010).

- Transport and handling** from storage point to chamber requires a correct design to guarantee fuel flux and dose. It depends on physical properties of the fuel, distance, risk of dust explosions and costs (Van Loo and Koppejan, 2010). Some of the most widely used handling systems are **belt conveyors** that allow high fuel flow and long distances, but are expensive. **Augers** or **screw conveyors**, are the most common transport systems from pellet stores to chambers. They cover distances up to 45 m, and are a cheap, flexible and closed transport system, providing a good solution for powdery, homogeneous fuels under 50 mm, such as wood pellets. It also requires higher power supply than belt conveyors. Other chance is **pneumatic conveying**; that requires homogeneous, small-sized material that can flow easily, meaning a good option for pellet burners. If silo reloading is to be done using this system, walls must be protected by adding some deflectors to avoid abrasion due to solids tracking.
- The aim of this work is not to give construction solutions. Many interesting works such as that of Ravenet's (1992) or Dai and Grace (2011) does so. Rather, our aim is to obtain an approach to determine which of the studied biomass fuels is economically more profitable, taking in account design and construction costs

2. Material and methods

2.1. Samples

Physical characterization was tested on a sample of proximately 250 g for 12 different brands of commercial wood pellets, named as **WP1–WP12**. For brand WP1, three different batches were used, named as **WP1B1–WP1B3** and a further six batches were studied for WP2, named as **WP2B1–WP2B6**. In addition to this, another **four** types of commercial pellets were studied, beetroot pellets (**BPs**), pine and pine apple leaf pellets (**P&PLPs**), pine pellets (**PPs**) and straw pellets (**SPs**) aiming to compare these physical parameters in a wide range of densified commercial densified fuels. Furthermore, one brand of commercial briquette was analyzed and

Table 1
Review of pellets analysis standards in different countries.

Parameter	Normative
Dimensions (size/shape)	PVA (Aut), ÖNORM M7135 (Aut), SS187120 (Swe), DIN 51731 (Ger), CTI-R 04/5 (Ita).
Bulk density	SS 187120 (Swe), ASTM E873-82 (USA), UNE-EN 15103 (Spa)
Particle density	PVA (Aut), ÖNORM M7135 (Aut), DIN 51731 (Ger), UNE-CEN/TS 15150 (Spa)
Durability	ASAE S269.4 (Aus), ONORM M7135 (Aut), ASTM E1288-89 (USA), UNE-EN15210 (Spa)
Impact resistance	ASTM D440-86 (USA)
Particle size distribution	ANSI/ASAE S319.4 (Aus), ASTM E828-81 (USA), UNE-EN 15149 (Spa).
Moisture	ASTM E871 (USA), UNE-EN 14774 (Spa), SS187170:3 (Swe)
Higher heating value (HHV)	ASTM E711 (USA), UNE-EN 14918 (Spa), SS ISO 1928:1 (Int)

PVA – Austrian standard (Austrian Pellets Association). ÖNORM – Austrian normative. SS – Swedish normative. ANSI/ASAE – Australian normative. ASTM – US normative. DIN – german normative. UNE-EN – Spanish (transposed from EU) normative.

the bulk density experiments were carried out on other 34 biomass fuels obtained from the Spanish market, in an attempt to compare these values and their marginal costs with those obtained for densified fuels. Some examples of these samples are shown at Fig. 2.

2.2. Physical properties determination

- The average **dimension** for each studied sample was determined following the ÖNORM M 7135 standard (Carone et al., 2011) by measuring the length and diameter of 20 randomized chosen pellets for each sample. For briquettes the same process was used, but only three length and diameter measurements were taken per sample.
- **Bulk density determination** is applied to both densified and non-densified fuels, and requires the exact weight and volume of a 50 g sample (Oberberger and Thek, 2004). Weight was obtained using Mettler-Toledo AG 204 scales, with four decimal point precision, and volume using a graduated glass. Bulk density and average deviation are provided from three measures per sample.
- **Particle density determination** is developed on pellets and briquettes by using a stereometric method, based on the measure of the diameter, length, mass and volume of a sample (Carone et al., 2011). Length and diameter measurements are developed twice and diameter six times, two at each end and twice more in the middle.
- **Durability determination** is evaluated following a procedure developed by Pis et al. (1988). Samples of around 40 pellets were introduced into a rotating drum equipped with two opposite inner baffles arranged perpendicularly to the cylinder wall. The rotation speed was set at 35 rpm. Each pellet sample was analyzed after 500, 1000, 1500, 2000, 2500 and 3000 revolutions. Following removal from the drum, the sample material was screened using a 2 mm sieve. Particles smaller than 2 mm were then weighed and the **Abrasion Index** (AI) was calculated using the following equation:

$$AI = \frac{M_0 - M_R}{M_0} \cdot 100 \quad (1)$$

where AI is the abrasion index, M_0 the initial mass and M_R is the retained mass. AI was obtained by the rotating drum test as the mean

value of three replications. It is considered that the lower the AI, the better the pellet quality. AI has the opposite meaning to durability (DU), which is obtained as follows:

$$DU = 1 - AI \quad (2)$$

Once the durability value has been determined, it can easily be related to the number of revolutions, and second-order fine tuning models were obtained. After this, by applying mathematical derivatives, the abrasion limits for each sample can be calculated.

2.3. Store and transport system design

- **Store design** costs depend on its size, and thus on the fuel's physical characteristics (main bulk density) and higher heating values. A general expression to determine the size of a silo was used:

$$S_c = \frac{P \cdot t}{HHV \cdot \mu \cdot BD} \cdot 3600 \quad (3)$$

where S_c is the store capacity measured in m^3 , P is the estimated energy requirement of the system in kW, t the storage time required in days, NCV is the net calorific value, or the one obtained if gaseous water is considered as a product, and energy required to evaporate water is not computed as heat. It can be considered as 85% of the HHV measured in kJ/kg, μ the combustion efficiency, considered as 85% for wood and BD the bulk density of the fuel, measured in kg/m^3 .

The price of the screw can be approximated as done by Walas (1990):

$$C = 0.40 \cdot L^{0.48} \quad (4)$$

where C is the screw conveyor price (in dollars) and L the length measured in feet. This equation is valid only for screws between 0.18 and 2.54 m (7–100 ft).

- The objective of the **transport system design** is to determine the economic viability of the considered fuels by comparing the energy consumptions of a screw conveyor designed to feed a domestic chamber of 1000 kW. Baquero (1985) presents different ways to estimate the dimensions and power consumption of the screw conveyor that best fits the required application.

Table 2

Results obtained for the dimensions determination.

Sample	Length (cm)	Diam. (cm)	L/D	Mass (g)	Density (g/cm ³)
BP	3.0 ± 0.8	1.10 ± 0.03	2.8 ± 0.7	3.4 ± 0.8	1.18 ± 0.06
BRI	31 ± 1	9.3 ± 0.1	3.33 ± 0.04	2184 ± 89	1.03 ± 0.02
P&PLP	1.6 ± 0.3	0.61 ± 0.01	2.6 ± 0.5	0.5 ± 0.1	1.16 ± 0.03
PP	2.1 ± 0.4	0.62 ± 0.01	3.4 ± 0.6	0.8 ± 0.1	1.23 ± 0.04
SP	1.3 ± 0.3	0.86 ± 0.02	1.5 ± 0.3	0.7 ± 0.2	1.0 ± 0.1
WP1B1	1.5 ± 0.4	0.64 ± 0.01	2.3 ± 0.7	0.5 ± 0.2	1.08 ± 0.07
WP1B2	1.6 ± 0.3	0.64 ± 0.01	2.41 ± 0.05	0.5 ± 0.1	1.08 ± 0.08
WP1B3	1.7 ± 0.6	0.62 ± 0.01	2.8 ± 0.9	0.6 ± 0.2	1.12 ± 0.07
WP2B1	1.5 ± 0.4	0.63 ± 0.01	2.5 ± 0.7	0.5 ± 0.1	1.10 ± 0.09
WP2B2	1.5 ± 0.4	0.63 ± 0.01	2.4 ± 0.06	0.5 ± 0.1	1.11 ± 0.08
WP2B3	1.4 ± 0.5	0.63 ± 0.02	2.3 ± 0.8	0.5 ± 0.2	1.11 ± 0.09
WP2B4	1.7 ± 0.7	0.61 ± 0.01	3 ± 1	0.6 ± 0.2	1.17 ± 0.07
WP2B5	1.4 ± 0.4	0.61 ± 0.01	2.3 ± 0.7	0.5 ± 0.2	1.2 ± 0.4
WP2B6	1.2 ± 0.4	0.62 ± 0.01	1.9 ± 0.7	0.4 ± 0.2	1.2 ± 0.1
WP4	1.5 ± 0.2	0.63 ± 0.01	2.4 ± 0.3	0.52 ± 0.06	1.11 ± 0.06
WP5	1.7 ± 0.3	0.70 ± 0.07	2.4 ± 0.6	0.6 ± 0.1	0.9 ± 0.2
WP6	1.8 ± 0.4	0.61 ± 0.01	2.9 ± 0.7	0.6 ± 0.2	1.2 ± 0.1
WP7	1.9 ± 0.4	0.62 ± 0.02	3.1 ± 0.6	0.7 ± 0.1	1.14 ± 0.09
WP8	1.4 ± 0.1	0.65 ± 0.02	2.2 ± 0.2	0.45 ± 0.05	0.97 ± 0.09
WP9	2.1 ± 0.50	0.64 ± 0.01	3.2 ± 0.7	0.8 ± 0.1	1.2 ± 0.1
WP10	1.4 ± 0.4	0.64 ± 0.01	2.1 ± 0.7	0.5 ± 0.2	1.1 ± 0.1
WP11	0.7 ± 0.2	0.62 ± 0.01	1.2 ± 0.4	0.3 ± 0.1	1.1 ± 0.1
WP12	1.0 ± 0.5	0.62 ± 0.02	1.5 ± 0.8	0.3 ± 0.2	1.1 ± 0.1

Table 3

Results obtained for bulk density analysis of several biomass samples.

Sample	BD	HHV	Moisture	Sample	BD	HHV	Moisture
Almond shell	373 ± 10	18,275	8.68	Straw pellets	565 ± 20	16,584	7.3
Almond shell ^a	494 ± 14	18,275	8.68	Thistle	29 ± 2	17,747	11.6
Barley	770 ± 17	16,519	9.9	Triticale ^a	190 ± 28	16,645	9.8
Beech Wood ^a	167 ± 2	18,220	10.2	Vine orujillo	143 ± 18	17,742	9.5
Beetroot pellets	539 ± 23	15,095	12.5	Vine shoot chips	119 ± 55	14,631	22
Building wastes chips	149 ± 24	18,279	7.9	Wheat	813 ± 16	16,325	10.3
Cherry tree wood ^a	198 ± 12	17,734	7.7	Wheat bran	235 ± 5	17,370	9.0
Chestnut tree shaving	88 ± 16	17,616	8.35	Wheat straw	27 ± 3	17,344	7.7
Chestnut tree wood ^a	162 ± 8	17,485	9.1	Wood chips	189 ± 35	15,162	25.6
Cocoa beans husk	234 ± 20	17,313	8.8	WP1B1	651 ± 24	18,074	8.9
Coffee husk	34 ± 1	18,326	9.6	WP1B2	553 ± 22	18,662	7.7
Eucalyptus chips	200 ± 28	16,838	11	WP1B3	500 ± 18	18,828	8.2
Holm oak branch chips	166 ± 15	17,181	11.1	WP2B1	543 ± 13	18,897	7.9
Maize (raw cereal)	773 ± 52	16,429	11.1	WP2B2	542 ± 27	18,756	7.0
Maize ^a	588 ± 78	16,429	11.1	WP2B3	565 ± 7	18,965	7.73
Miscanthus ^a	201 ± 3	18,072	7.53	WP2B4	612 ± 49	18,880	5.56
Olive stone	742 ± 42	17,884	11	WP2B5	619 ± 36	18,825	8.1
Olive tree pruning	112 ± 8	17,342	8.7	WP2B6	618 ± 35	18,825	7.6
P&PLP	676 ± 14	18,147	8.2	WP3	288 ± 29	18,160	8.76
Pine chips	170 ± 3	19,427	10.25	WP4	639 ± 12	18,303	6.84
Pine cone heart	238 ± 37	16,440	23.1	WP5	469 ± 23	17,897	7.96
Pine cone leaf	392 ± 12	18,633	9.14	WP6	648 ± 37	18,552	7.04
Pine kernel shell	535 ± 17	18,893	8.33	WP7	562 ± 33	18,525	7.33
Pine pellets	647 ± 42	18,840	6.75	WP8	570 ± 12	17,871	8.4
Pine shaving	33 ± 5	19,793	9.2	WP9	504 ± 43	18,717	7.7
Rice husk	107 ± 9	15,899	7.27	WP10	593 ± 25	18,504	8.4
Rye	831 ± 21	16,141	10.76	WP11	650 ± 22	N/D	N/D
Sainfoin ^a	233 ± 34	16,412	9.6	WP12	588 ± 21	N/D	N/D
Sawdust	125 ± 8	18,016	11.3	WP average	589 ± 128	18,218	7.7
Sorghum ^a	204 ± 23	11,872	6.1				

HHV is the average higher heating value measured in kJ/kg, moisture is an average value measured in weight percentage (García et al., 2012).

^a Indicates grinded sample. BD means bulk density measured in kg/m³.

$$P = \frac{Q \cdot L \cdot BD \cdot f}{80} + \frac{Q \cdot BD \cdot h}{270} \quad (5)$$

where P is the power requirements measured in HP, L the length of the conveyor in meters, BD is the bulk density in Mg/m³, f a factor dependent on the fuel, with values between 1.2 and 1.6 and h the height difference between both sides of the screw.

3. Results and discussion

3.1. Dimensions determination and particle density

The results obtained for the average length, diameter, length/diameter ratio, mass and density of the measured samples are presented in Table 2. As can be seen, the vast majority of the studied samples, with the exception of beetroot pellets, present quite homogeneous characteristics, with length, diameter and L/D ratio approximately 1.5, 0.62 cm and 2.4, respectively. Mass and density values are close to 0.7 grams and 1.1 g/cm³.

3.2. Bulk density

The results obtained for bulk density are shown in Table 3. As can be seen, values found in the literature for densified fuel's bulk density in the range from 650 to 800 kg/m³ (Kaliyan and Morey, 2009; Mani et al., 2003) are far too optimistic.

The best results arising in this work were those obtained for cereals (maize, barley and wheat grain) with values over 750 kg/m³. The only densified samples which approach expected values are P&PLP, WP1, WP6 and WP11. Values corresponding to densified biofuels are much higher than raw biomass (chips, shavings, sawdust), which rarely approaches 200 kg/m³, with the entailing logistic problems. Shells can be found at an intermediate level, with values close to 500 kg/m³.

Some of the samples were tested with and without grinding. As can be seen this process improves the results. Pelletization increases bulk density from 150 kg/m³ obtained for raw wood or chips to nearly 600 kg/m³. These facts clearly show the need for of a previous adequate pretreatment of the raw material and the importance of grinding it if used as a fuel in combustion process.

3.3. Durability

The results obtained for the durability experiments are shown in Figs. 3 and 4. In Fig. 3, seven batches of pellets from two commercial brands were analyzed.

The worst batch for each brand was selected and compared in Fig. 8 with each of the other types of pellet. All the experimental data were fitted to a second-order polynomial equation (type $y = a + bx + cx^2$), where "y" is the Abrasion Index (AI) and "x" the number of revolutions undergone by the samples in the tumbling device used and described in 2.5. In these equations, the first derivative was taken and equaled to 0 to determine the number of revolutions needed to obtain the maximum abrasion index, from which the durability, DU, is evaluated by means of Eq. (2). The results are shown in Table 4.

As can be seen, all of the studied samples, except WP3 (20%), WP5 (62%) and P&PLP (93.5%) exceed the 95% quality criterion for pellet durability suggested by Richards (1990). The last of the mentioned samples comes quite close to this value, while the other two, which clearly fail to satisfy the criterion, should be considered as pellets of poor durability, which could generate some of the problems mentioned in 1.4.

3.4. Storage and transport system

As previously discussed, choosing one or another fuel has an economical influence, as this may change from country to country.

Fig. 2. Morphology of several biomass fuel samples. 1. Beetroot pellets. 2. Straw pellets. 3. Pine and pine apple leaf pellets. 4. Wood pellets. 5. Cocoa beans husk. 6. Almond shell. 7. Vine orujillo. 8. Pine cone leaf. 9. Pine cone heart. 10. Coffee husk.

Fig. 3. Abrasion index for WP1 and WP2 different batches.

Fig. 4. Abrasion index for every studied pellets brand.

Table 4
Results obtained for durability analysis.

Sample	<i>a</i>	<i>b</i>	<i>c</i>	<i>R</i> ²	Durability
BP	0.016	0.00030514	−1.7143E−08	0.999	98.63
P&PLPP	0.757	0.00265421	−3.0643E−07	0.999	93.50
PP	0.225	0.00083536	−8.3571E−08	0.998	97.69
SP	0.299	0.00123807	−1.1357E−07	0.998	96.33
WP1L1	0.141	0.00066193	−3.5E−08	0.999	96.73
WP1L2	0.07	0.00036	−2.2857E−08	0.999	98.51
WP1L3	0.04	0.000436	−0.00000004	0.999	98.77
WP2L1	0.072	0.00027386	−2.1429E−08	0.998	99.05
WP2L2	0.149	0.00041164	−2.9286E−08	0.998	98.40
WP2L3	0.16	0.00030743	−1.7143E−08	0.999	98.46
WP2L4	0.052	0.00026714	−2.5714E−08	0.999	99.25
WP3	52.9	19.8	−3.57	1.000	19.65
WP4	0.234	0.00152686	−1.5429E−07	0.999	95.99
WP5	14.681	0.01691979	−3.0907E−06	0.986	62.16
WP6	0.1875	0.000605	−0.00000007	0.999	98.51
WP7	0.196	0.00097743	−7.7143E−08	0.998	96.71
WP8	0.436	0.00175914	−1.8571E−07	0.999	95.40
WP9	0.428	0.001184	−1.0286E−07	0.998	96.16
WP10	0.082	0.00043171	−0.00000002	0.999	97.59
WP11	0.135	0.00065821	−5.5E−08	0.998	97.90
WP12	0.1	0.00070743	−5.7143E−08	0.999	97.71

Therefore, a calculus base must be chosen to obtain a relative comparison that can be generalized. Here, a buried bunker designed to feed a 1000 kW chamber during seven days is considered. The optimal structure is a cubic store. Store-chamber transport is done using a 0.23 m diameter screw, sloped 25°, with a fuel flux up to $2.3 \times 10^{-3} \text{ m}^3/\text{s}$ working at 80% capacity and 5.24 rad/s would cover the needs of every studied sample (Walas, 1990), as the store size will change from one to another fuel, the length of the screw, and thus, its cost, will be also influenced. The size of the buried stores is also calculated for each of the fuels considered, this is highly influenced for the bulk density and HHV, which are obtained from a previously developed database (García et al., 2012). Fig. 5 shows the results obtained for the bunker capacity and power required by the screw conveyor for each of the tested samples. For wood pellets, the average value obtained from all samples and batches was used for the estimation.

As can be seen, there are huge differences in the silo size, depending on the selected fuel, from stores of $50\text{--}70 \text{ m}^3$, which implies 4 m per side (for fuels such as cereals, olive stones or some varieties of pellets) to stores of more than 1000 m^3 , which means more than 10 m in side, for other ones like coffee husk, pine shaving, thistle or wheat straw. These dimensions make these fuels

Fig. 5. Results obtained for the bunker capacity and power required by the auger.

Fig. 6. Fixed and variable relative costs for the tested biomass samples.

inviability, if only for logistic and construction reasons. Such large stores require a longer screw conveyor, that may vary from 10 to 30 m which will directly influence power requirements, between 1.2 and 4 kW, but this fact will not be, a priori, as important as the manufacture and design costs of the proper screw.

To compare which fuel was better overall, these data were supplemented with “civil work” prices needed for silo construction (PREOC, 2012), biomass transport costs (McGowan et al., 2009) and Spanish electricity tariffs. Costs were divided in two; “fixed costs”, which are one-time capital costs for the screw conveyor and silo components, and “variable costs”, which are recurring costs for electricity consumption and refilling the silo. As prices in each country may differ, the comparison is made taking as a base the fuel with the lowest tariff in each aspect (rye for fixed costs and olive stones for variable costs) to obtain a qualitative comparison. As can be determined in Fig. 6, the adequate selection of the fuel is of capital importance in processes of the same size. Thus choosing non-densified fuels, with low energy density, such as straw, thistle, coffee husk or shavings may increase fixed costs by over 10% and variable costs by over 20%.

On the other hand, some wastes such as almond shell or olive stone, cereals or pellets present an optimum relationship, being those with lowest costs in both aspects. This is of course, subjected to availability and price of the fuel in each specific region.

4. Conclusions

Most of the studied commercial samples are homogeneous in shape, size and density, making them easy to manage in different kinds of transport systems.

Bulk density studies did not produce results as successful as expected for densified fuels. In this aspect the highest results belonged to cereals and only four brands of pellets approached the commonly referred to as “average” value of 650 kg/m³.

Durability experiments showed that the quality of the commercial samples can be considered, generally, as quite high, exceeding 95% in each case.

Preliminary economic research showed that for the same system, hard and densified fuels demonstrated savings of over 10% in fixed costs and 25% in variable costs.

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