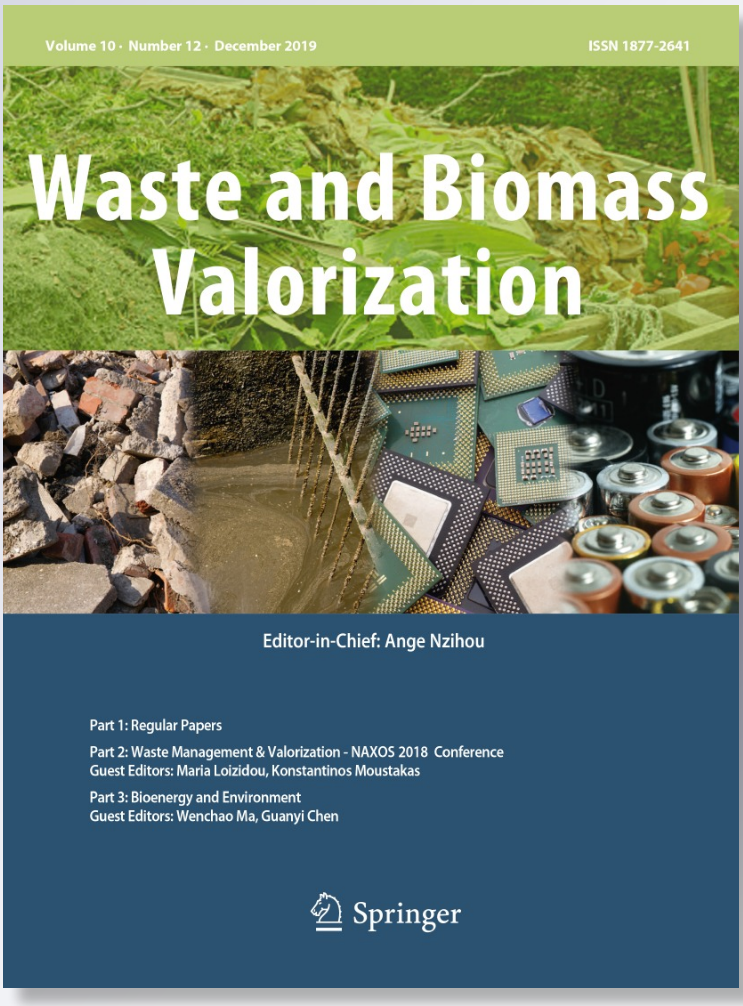
A Feasible Application of Circular Economy: Spent Grain Energy Recovery in the Beer Industry

I. Ortiz, Y. Torreiro, G. Molina, M. Maroño & J. M. Sánchez

Waste and Biomass Valorization

ISSN 1877-2641
Volume 10
Number 12

Waste Biomass Valor (2019)
10:3809-3819
DOI 10.1007/s12649-019-00677-y



Springer

Waste and Biomass Valorization (2019) 10:3809–3819
https://doi.org/10.1007/s12649-019-00677-y

ORIGINAL PAPER

A Feasible Application of Circular Economy: Spent Grain Energy Recovery in the Beer Industry

I. Ortiz[1] · Y. Torreiro[1] · G. Molina[1] · M. Maroño[1] · J. M. Sánchez[1]

Received: 12 November 2018 / Accepted: 15 April 2019 / Published online: 19 April 2019

Abstract

The generation of residual streams and wastes is a common constant in all productive processes. The brewing sector generates a large quantity of residual by-products which can be sustainably reused within the industry to contribute to cover the energy requirement of the process and at the same time to contribute to minimize the amount of waste that is sent to landfills. In this paper the feasibility and advantages of incorporating a stage for energy recovery from some of the solid wastes generated during the process as part of the circular economy approach is presented. La Cibeles, a local small size beer process is taken as a real example. In a brewing process the main wastes that are produced are: grain husks, yeast and CO_2. Out of the three, the most important one is the grain husk or brewers' spent grain that can make around 85% of the total waste of a brewery. The results presented in this study show that, by gasification of brewers' spent grain, not only the final volume of the residue to be disposed is considerably minimised, but also it is possible to obtain a net economic saving of around 22% in the consume of fossil fuels used in the brewing process when the syngas produced is used for heat generation.

Keywords Circular economy · Energy recovery · Waste gasification · Beer bagasse · Brewers' spent grain

Statement of Novelty

In this article a real example of energy recovery from waste in the beer industry is presented. We provide a technological alternative process that can be economically attractive for an industrial beer process: the recovery of the energy contained in the waste and its use onsite following the sustainability principle of the circular economy. Gasification was the waste-to-energy technology selected and all the process steps from waste generation and conditioning to energy production and final application were described and the application of the proposed solution to a local craft brewery is presented. This article shows how gasification of beer bagasse in the beer industry can reduce the external energy requirements covered by fossil fuels

Introduction

Brewing sector holds a strategic economic position with annual production in Europe of 400 million hectolitres which places EU as the second largest beer producer in the world [1]. The European brewery sector is extremely varied, including world´s largest brewing companies but also numerous small and mid-size, independent breweries. In 2013 there were 4460 breweries in the European Union and this number increases every year and the total beer sales in 2010 reached Euro106 billion, which corresponded to 0.42% of the GNP (gross national product) of the European Union [2].

The craft brewing industry in many countries has undergone a rapid expansion in the number of breweries and has gained market share from the larger (inter)national breweries [3]. In Spain, craft breweries production increase 36% in 2017 with 170.000 hectoliters distributed in 477 companies. In 2018 an increase of 38% was expected and this trend is expected to be maintained in the medium term as evidence in the fact that in April 2018 the number of craft breweries reached 511 [4].

The most significant environmental issues of this industrial sector include water consumption, wastewater, solid

---

✉ I. Ortiz
isabel.ortiz@ciemat.es

[1] Sustainable Thermochemical Valorisation Unit, CIEMAT, Adv. Complutense 40, 28040 Madrid, Spain

waste and by-products generation (such as yeast), energy use and emissions of CO_2 to the atmosphere. In general, brewing processes are energy intensive and involve the use of large volumes of water and large production of solid wastes (< 50 kg/m^3) [5] which in the context of a linear economy approach will finally end up in landfills.

However, in a circular economy approach, a new perspective allows to see wastes as resources, useful for other processes, within or without the industry that produces them. Approaches following the circular economy principles could provide cost savings up to 20% for various industrial sectors such as food, beverages, textiles and packaging [6]. Moreover, the annual net benefits for EU-27 business of implementing resource-efficiency/circular economy measures such as waste prevention or recovery of materials in an industrial process can represent an average of 3–8% of annual turnover [7].

In this context the brewery industry is following different approaches for increasing energy efficiency and reducing wastes (wastewater, solid wastes) and CO_2 emissions. Both on-site and off-site solutions are nowadays being applied [8]: as an off-site solution for solid wastes many breweries have built efficiency and waste reduction into their core business by working with local farmers to reuse the brewers spent grain (BSG) mostly for feeding bovine cattle. For on-site solid waste treatment two options are available: composting and a waste-to-energy approach, including anaerobic digestion and thermochemical conversion processes (incineration, pyrolysis, gasification). Up to now the most common waste-to-energy system used in the brewery industry is anaerobic digestion but this option may not be feasible for smaller breweries not being able to produce the quantity of waste needed to make this approach cost-neutral. Therefore, alternative solutions based on waste-to-energy can be considered as a suitable option in line with the position of the CE regarding the transformation of wastes in energy and its role on the circular economy [9].

In this paper the feasibility and advantages of recovering the energy contained in wastes as one stage in the application of the circular economy approach is presented taking La Cibeles as a real example, a local small size craft brewery. In the brewing process the main wastes that are produced are: grain husks, yeast and CO_2. Out of the three, the most important one is the grain husk or BSG that can account for around 85% of the total waste generation of a brewery. Different applications have been studied for valorisation of BSG. Some of them have been summarized in Table 1. Due to its content in sugars and proteins, a significant part of BSG is used for animal feeding, mostly for bovine cattle, but in some cases this option cannot be the most favourable one: depending on the amount of residue produced, beer makers may need to paid for its removal and if the brewery is far away from the end user farm it is also frequent that farmers only accept to pay the price of transportation for removing the bagasse and this option can be expensive [10].

Among the waste to energy technologies available, the anaerobic digestion is the most common one for BSG. But the initial investment, CAPEX for acquiring the equipment required is high as well as technical know-how to keep the operation running smoothly is needed which may not be feasible for small breweries. In the same way, small breweries may not produce the quantity of waste needed to make the waste-to-energy system a cost neutral or positive investment [8].

In this work we provide a technological alternative process that can be economically attractive for an industrial beer process: the recovery of the energy contained in the waste and its use onsite following the sustainability principle of the circular economy. The application of the proposed solution to La Cibeles, a Spanish local small beer producer is presented.

Table 1 Potential application of BSG

Uses	Issues	References
Animal feeding	- Cost of transporting - Unstable and susceptible to microbial contamination. Within three days (in summer even shorter) BSG cannot be used anymore as animal feed	[10] [11, 12]
Human diet (bakery products)	- Need pre-treatment (dried, converted to flour) - Only for application in coloured products - Incorporation of only small amounts (up to 100 g/kg) in food formulations has been recommended	[10]
	- Drying pre-treatment required - Dust and NOx emissions	[10, 12]
	- Pure digestion concepts suffer from low degradation rates and require long retention times because of high fibre and water contents - Expensive	[12]
	- Present poorer burning properties than those reported for sawdust charcoal, for example, because the ignition temperature is higher and the burning period is longer	[10, 11]

Approach and Methodology

Samples of BSG were provided by La Cibeles, a local craft brewer located in Madrid (Spain). The first step was the determination of the thermochemical potential of the beer bagasse in order to select the most suitable thermochemical technology for the maximization of energy recovery (combustion, pyrolysis or gasification). The determination of the most critical parameters including moisture, elementary composition, heating value (HV), etc., was performed by means of physicochemical and thermochemical characterization analysis which was carried out following the current European standards for biomass feedstock that are summarized in Table 2.

Based on the characterization results of the beer bagasse and on the analysis of the energy requirements of the process an evaluation of the suitability of the proposed solution was performed. For the energy requirement of the process real data have been used including bagasse generation (kg/m^3 beer produced); steam requirements for heating (kg/m^3 beer produced) and cooling necessities (kWh).

Finally, a flow chart of the proposed technical solution applied to the real case considered has been designed.

Table 2 Standards methods used for physicochemical characterization

Parameter	Standard
Proximate analysis	
Volatile matter	UNE-EN ISO 18123:2016
Ash	UNE-EN ISO 18122:2016
Moisture	UNE-EN ISO 18134-2:2016
Ultimate analysis	
C, H, N	UNE-EN ISO 16948:2015
S, Cl	UNE-EN ISO 16994:2017
Calorific value	UNE-EN ISO 14918:2011

Results

Brewing Process

The beer-brewing process studied consists of several subsequent steps summarised in Fig. 1. Essentially, the brewing process begins with the wort production. The milled barley malt is mixed with water in a mash tun to convert the malt starch in sugars. At the end of the process, two streams are obtained in the lautertun: the insoluble undergraded part of the barley malt grain or BSG and the wort. Then, the wort is transferred to the kettle where it is boiled with the hops. In the whirpool any malt or hop particles are removed and after that, the wort is cooled down and fermented in the fermentation tank. Yeast converts the sugars' wort into alcohol and carbon dioxide producing the beer. In this craft brewing process, steps like filtration or pasteurization, common in industrial processes, are not carried out. The main wastes from the brewing process are: BSG, yeast and CO_2. The most important one is BSG which means around 85% of the total waste of a brewery so this work is focused on the use of this byproduct.

Data from the craft brewery were collected by interviews and summarised in Table 3.

The energy requirements of the brewing mainly come from the thermal energy used, on one hand to heat up the water for the mash and lautertun and to generate the steam necessary for the boiling step and on the other hand to cool down the wort before the fermentation step. It is estimated that the 75% of the energy needed in the brewing process is used in thermal form and only 25% is required as electrical energy [13]. From the data of Table 3, it can be understood that both requirements are similar but it has to be taken into account that part of the electricity is used to heat up and cool down the water used in the process.

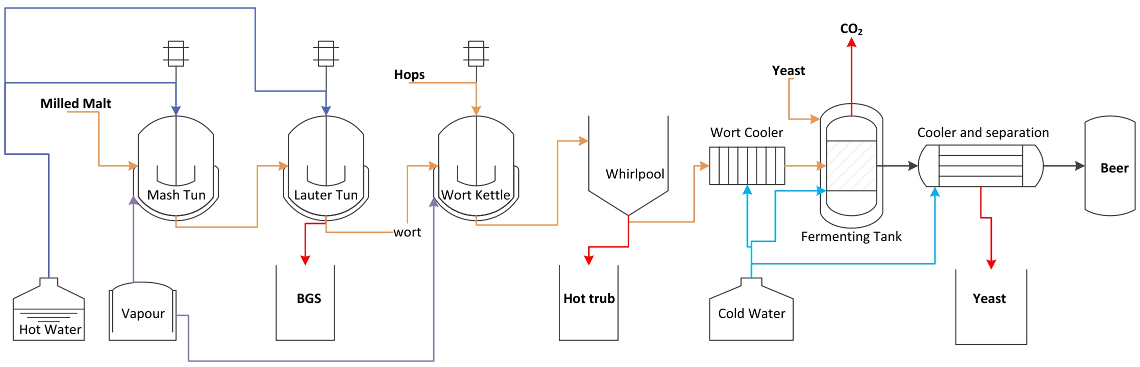


Fig. 1 Schematic beer brewing process

Table 3 Figures of brewing process

Parameter	Quantity
Beer annual production	504 (m^3)
Raw materials	
Water	6 (m^3/m^3 beer*)
Malt	200 (kg/m^3 beer)
Hops	–
Yeast	50 (l/m^3beer)
By-products produced	
BSG	200 (kg/m^3 beer)
Hot trub	3 (kg/m^3 beer*)
Yeast	0.2 (m^3/m^3 beer*)
CO_2	33 (kg/m^3 beer*)
Energy requirements	
CO_2 for transfer	3.7 (kg/m^3 beer)
Electricity	238 (kWh/m^3 beer)
Gasoil	371 (kWh/m^3beer)

*Estimated

BSG Composition

BSG is composed by the mixture of the husks that cover the original barley malt grain with part of the pericarp and seed coat layers that are obtained as residuals solid mater after the wort extraction step [10]. From an energy point of view, the most important parameters to be taken into account are the calorific value and the moisture content. To consider thermochemical valorisation as a valuable solution, the fuel must present some specific characteristics. In particular, a high calorific value (> 15 MJ/kg) is required and moisture needs to be kept in the range of 10–15%. Table 4 summarises the physicochemical characterisation results obtained for the BSG considered in this study. The results of two more samples of BSG and wood pine chips (WPC), taken from literature, are also added for further comparison. Although it is reported that chemical composition can be affected by factors such as the variety of the barley, the harvest time, cultivation conditions, malting and mashing conditions and the use of other cereals (adjuncts) for the wort elaboration [14], no significant variations were observed in ultimate and proximate analysis.

As it can be seen in Table 4 the results of the characterization analysis of BSG show promising perspectives for its thermochemical valorisation. BSG shows a high calorific value in dry basis (21 MJ/kg) which is in the same range to other biomass as olive pits or fir mill [18] which are commercially available for energy applications.

Due to the intrinsic characteristics of the beer making process, which essentially can be regarded as boiling, the moisture of the BSG is very high (76%). Consequently, a drying stage is essential since high moisture not only reduces the energy content but also increases the residue volume, the handling and transportation cost, the instability of BSG and the microbial contamination by filamentous fungi [11].

Furthermore, for energy applications other parameters are also important such as the ash and volatile content and the presence of some inorganic elements as nitrogen, sulphur and chlorine. As it is shown in Table 4, the results obtained for BSG characterisation are relatively similar to those found for a typical biomass used in thermochemical processes (wood pine chips), especially in terms of volatile fraction and fixed carbon content. Moreover, the BSG has not only low ash content but also low content of alkaline elements, which reduces the risk of operational problems due to sintering phenomena. Therefore, and in the same way than when WPC are used as fuel, a good performance can be expected for BSG in a thermochemical process.

The content of nitrogen, sulphur and chlorine are important to predict the formation and presence of contaminants in the syngas generated and therefore the need of downstream cleaning systems. For the BSG studied, the nitrogen and sulphur content are relatively high compared with the typical values found in wood chips, so these elements will have to be taken into account in the design of any process solution.

BSG Drying

As it was mentioned above, the moisture content of BSG is the major limitation in the energy balance so this step should be designed carefully. BSG drying could be carried out using different technologies, (thermal treatment, pressing, freeze-drying…). The selection of the most suitable one depends on numerous factors (quantity, final application of BSG…). BSG pressing can reduce the water content to 20–30% using membrane filter press. Although commercial systems are available their cost requires continuous operation and therefore it is unlikely to be affordable to small scale brewers [19]. In the same way, freeze-drying is economically unadvisable [14]. So, in our case thermal treatment for BSG drying was chosen.

With the aim of reducing the cost of drying, a hybrid solar-biomass greenhouse has been selected providing thus a renewable source for heat exchange. With this system the biomass can be dried to 10–15% using solar radiation and other low temperature sources such as hot water from engine cooling systems or from heat exchangers of combustion gases. To achieve the maximum water evaporation target, this system counts with four heat sources: solar radiant heat directly focused on the biomass bed, hot air from solar collector panels (thermosolar), radiant floor and hot air from biomass as a fuel support [15]. Pérez et al. [15] studied BSG drying in this system and found that the moisture content

Table 4 Physicochemical characterization of BSG and biomass of reference

	BSG studied	BSG [15]	BSG [16]	WPC [16]	WPC [17]	
Moisture	76	81	–	3.84*	8.8*	wt% a.r.
Ash	3	4	4.4	0.60	0.5	wt% d.b.
Volatile matter	79	77	–	80.0	83.1	wt% d.b.
Fixed carbon	18	19	–	19.4	7.6	wt% d.b.
HHV	21	21	22	19.6	18.5	MJ/kg d.b.
LHV	19	19	20	20.9	19.1	MJ/kg d.b.
Ultimate analysis						
C	48.7	50.4	51.1	51.8	49.6	wt% d.b.
H	6.8	6.5	6.9	6.1	6.5	wt% d.b.
N	3.5	4.4	4.7	0.3	0.16	wt% d.b.
S	0.24	0.3	0.4	0.01	0.02	wt% d.b.
Cl	0.04	0.01	–	–	0.02	wt% d.b.
O	37.6	34.3	32.5	41.2	43.3	wt% d.b.
Ash composition						
Al_2O_3	0.16	–	0.80	5.10	3.4	wt% ash d.b.
BaO	0.02	–	–	–	0.06	wt% ash d.b.
CaO	5.6	–	13.7	33.6	36.4	wt% ash d.b.
Fe_2O_3	0.48	–	1.30	2.14	1.4	wt% ash d.b.
K_2O	4.6	–	0.90	12.05	7.6	wt% ash d.b.
MgO	9.1	–	7.5	5.14	7.3	wt% ash d.b.
Mn_2O_3	0.16	–	–	–	1.4	wt% ash d.b.
Na_2O	0.26	–	0.20	0.19	0.92	wt% ash d.b.
P_2O_5	30	–	30.4	4.81	3.4	wt% ash d.b.
SO_3	0.77	–	–	1.62	3.5	wt% ash d.b.
SiO_2	35	–	42.7	23.53	11.8	wt% ash d.b.
SrO	0.032	–	–	–	0.040	wt% ash d.b.
TiO_2	0.012	–	–	0.06	0.11	wt% ash d.b.
ZnO	1.5	–	–	–	0.082	wt% ash d.b.

a.r. as received, *d.b.* dry basis

*Pellet

can be brought down to below 20% using more than 90% of renewable energy as shown in Table 5. Taken this work as reference, it has been estimated the total energy necessary for drying BSG from 76 to 10%. According to these estimations, only 192 kJ/kg_{BSG} is the energy required to be used from fossil fuels in this BSG drying process, as it is shown in Table 5.

Pelletizing

The pelletization process consists in the agglomeration by compression of fine powder or granules in pellets which have cylindrical shape of about 4–25 mm in diameter and up to 100 mm in length. Among the benefits of pelletization technique can be underline the higher energy density, easy to handle, minor transportation and storage cost and the possibility to use automatic feeding systems [20, 21]. However pelletization facilitates the feeding in the reactor unit, it is not a mandatory step if the feeding system is designed appropriately. In addition, pelletization may have the disadvantage of loss of material in some amount. Nevertheless, in

Table 5 Parameters of drying in hybrid solar-biomass greenhouse

Variable	Value literature [15]	Value estimated	
BSG yield	59.8		$kg_{w.b}/h$
BSG initial moisture	81	76	%
BSG final moisture	19.5	10	%
Evaporating yield	45.9	3415	$kg_{e.w.}/h$
Specific consumption	3415	91.5	$kJ/kg_{e.w}$
Renewable energy contribution	91.5		%
Energy consumption from non-renewable source		191.6	kJ/kg

w.b. wet basis, *e.w.* evaporated water this work this process has been taken into account to provide a more conservative approach.

The pelletization process consists of multiple steps including impurities elimination, drying, grinding, pelletizing and cooling. During pelletizing biomass is pressed against a heated die using a roller. Due to the high pressure, the biomass passes through the channels of the die and the temperature increases. Then, some components of the biomass (waxes) are released contributing to agglomerate the particles and form pellets [22]. Energy requirements for pelletizing depend on the raw material and the process conditions but in general it can be assumed that to produce 1000 kg of pellets it is necessary 3000 MJ [23]. This value accounts for the whole process, but in the case study the drying step had been already considered. Therefore based on the individual contributions for each steps of the process shown in Table 6, the energy required to manufacture 1000 kg of pellets is 900 MJ.

Energy Valorisation of BSG

Different technologies have been studied for valorisation of BSG as biogas production by anaerobic digestion [10], combustion [10, 12], pyrolysis [10], or gasification [15]. Most projects study the digestion of the raw whole BSG or just its incineration but no mature strategy is available yet [12] due to the fact that small breweries may not be able to produce the quantity of waste needed to make the waste to energy system a cost neutral or positive investment [8].

Anaerobic digestion is the most common waste to energy system because it seems the most favourable way due to the fact that no drying step is required. But, pure digestion concepts suffer from low degradation rates and require long retention times because of high fibre and water contents [12]. Besides that, not only the biogas production has a high OPEX but also a significant CAPEX. In addition to that, the technical know-how necessary to keep the operation running smoothly is high which may not be feasible for smaller breweries [8].

The other main alternative studied has been BSG combustion. BSG presents a good calorific value so it can be considered as a potential feedstock for incineration. However, for stable combustion conditions less than 45% of moisture is required [12] so drying pre-treatment is necessary. Heat generated by combustion could be used in the brewing process. However, BSG combustion generates emission of particles and toxic gases that contain nitrogen and sulphur dioxide [10, 12]. For these reasons, it is very important to take special care when performing the combustion of BSG in order to avoid or minimize these problems [10].

Table 6 Energy demand in the pelletizing process. Adapted from Pirragllia et al. [24]

Process step	Contribution (%)
Drying	70
Size reduction	4
Pelleting	13
Cooling	1
Screening	5
Miscellaneous	7

Taking into account that biogas production from BSG is limited to industrial breweries and the emissions problems of BSG combustion; the selected waste-to-energy technology for our case study was gasification. Compared to incineration, gasificationis regarded as more versatile, with a lower environmental impact and high electrical performance. In the particular case studied in this work, the technology selected has been gasification in a bubbling fluidized bed (BFB) gasifier, since it is a flexible mature technology, well-proven and implemented at commercial scale [25, 26]. Currently, there is not much information in literature regarding BSG gasification. Nevertheless, one of the fewest and most interesting works published on this topic to date is the one by Perez et al. [15]. These authors have recently studied the gasification of BSG with air in a BFB gasifier at pilot plant scale. They found that BSG gasification can be run process smoothly obtaining a syngas with a high calorific value ($2.7 - 8.1\mathrm{MJ}/\mathrm{Nm}^3_{\mathrm{db}}$ and low tar content. However, their work presents preliminary results since the operating conditions are not completely optimized yet, and therefore the gas composition is slightly far from the optimum. So, for the aim of this study, it was assumed that BSG dried present an analogue behaviour in the gasification process than the WPC due to the fact that physicochemical characterisation of BSG and WPC showed relatively similar results, especially in terms of volatile fraction and fixed carbon content. Only a slight different can be found in the ash content, being a little higher for the BSG but without any problematic element in its composition. In addition, the behaviour of the BSG in thermogravimetric analysis (TGA) is not very different to those shown by WPC.

In the field of gasification, it is well-known that in a typical BFB gasification process, and depending on the experimental conditions (ER, temperature, bed material, throughput, etc.), a syngas with a LHV between 4 and 8 $\mathrm{MJ}/\mathrm{Nm}^3_{\mathrm{d.b.}}$ can be obtained using air as gasifying agent [25]. Nevertheless, for the appropriate evaluation of the viability of BSG gasification in terms of circular economy, some data obtained from our previous experience in gasification and the results found in literature have been reviewed and summarized in Table 7.

According to the Corella and Sanz model [30], and assuming for BSG a similar behaviour than WPC under gasification conditions, using as fuel a biomass with moisture around 10%, and operating under a standard air

Table 7 Results obtained in gasification of Brewers' spent grain and comparison with biomass of reference

Parameter	Value estimated*	Pérez et al. 2017 [15]	Narvaez et al. 1996 [27]	Toledo et al. 2006 [28]	Arena et al. 2010 [29]	
Feedstock	BSG	BSG	WPC	WPC	Natural biomass	
Moisture	10.0	11.6	19.0–25.0	8.3	7.0	wt% a.r.
Ash	3.0	4.0	0.5–1.2	0.6	1.3	wt% d.b.
Operating conditions						
Bed temperature	850	720–860	790–810	850	810–880	°C
ER	0.30	0.16–0.25	0.26–0.47	0.30	0.23–0.28	
Gas composition						
H_2	12.0	2.1–3.6	7.0–9.5	13.9	12.2–12.5	% v/vd.b.
CO	17.5	7.4–13.1	10.0–18.0	20.9	16.9–17.9	% v/vd.b.
CO_2	15.0	11.9–13.1	12.0–15.0	12.5	16.0–14.0	% v/vd.b.
CH_4	3.5	2.0–12.8	2.4–4.5	4.5	3.9–5.0	% v/vd.b.
C_2H_2		0.2–0.4			0.08	% v/vd.b.
C_2H_4	1.0	1.0–2.4	1.1–2.3	2.0	0.8–1.2	% v/vd.b.
C_2H_6		0.04—0.4			0.04–0.17	% v/vd.b.
Efficiency						
Ygas	2.2	1.85–2.36	2.1–2.5	2.2	1.8–2.1	$Nm^3/kg\ fuel_{daf.}$
Energy production						
LHV	6.0	2.7–8.1	3.7–6.6	7.0	5.9–6.8	MJ/Nm^3_{db}
Power generated	3.20	1.5–3.5	2.0–3.0	3.90	3.4	kWh_{th}/kg fuel

*Values obtained using the model of Corella and Sanz [30], and confirmed according the Nikoo's approach [31]

gasification conditions (ER = 0.30, T = 850 °C and silica sand as bed material), the BSG gasification process generates a syngas with a LHV = 6.0 $MJ/Nm^3_{d.b.}$, composed mainly by H_2 (≈ 12% $_{v/v}$), CO (≈ 17.5% $_{v/v}$) and CO_2 (≈ 15% $_{v/v}$), with a gas yield around 2.2 $Nm^3_{d.b.}/kg\ fuel_{daf}$ and a relatively low tar content (below 4 $g/Nm^3_{d.b.}$), as it is shown in Table 7, col. 1. This theorical result obtained using the Corella and Sanz model has been confirmed in two different ways: (i) theoretically, according to simulation process developed by Nikoo et al. [31], which provide a very similar gas composition (11.7% H_2, 18.2% CO_2, 13.8% CO, 4.2% of CH_4 and 1.2% of C_2H_4) with a slightly lower LHV (5.88 $MJ/Nm^3_{d.b.}$ in this case), and (ii) by comparing with the experimental results already available in literature, as it is summarised in Table 7.

Thus, with this syngas obtained from BSG gasification with a LHV = 6.0 $MJ/Nm^3_{d.b.}$ the amount of energy that can be obtained is 3.2 kWh_{th}/kg fuel, which can be used in the energy requirements of the brewery, reducing in this way the energy demand of the facility. However, it must be taken into account that the gasification process consumes some amount of energy for its operation. Among the literature which study this consumption, in this work it is considered the study by Sahoo et al. [32] which studied the energy requirement for gasification of sugar bagasse that has a very similar composition compared with BSG. Based on this work it has been assumed that the energy necessary for the gasification process could be around 1 kWh_{th}/kg. Nevertheless, the net energy balance of the air gasification process continues being favourable, producing 2.2 kWh_{th}/kg fuel.

Other approach which should be mentioned in the context of circular economy and near to zero-waste generation processes is the use of the CO_2 stream in the gasification process, since CO_2 produced by fermentation is another main waste of the brewery. Although its demand in several applications, including the transfer of the wort to the different tuns, is great; in most breweries a large proportion, if not all, is allowed to escape into the atmosphere [33]. Several ways of reuse following a circular approach can be envisaged. On the one hand, reutilization in the brewing process itself would imply the necessity of deep purification and compression, and consequently this option would be costly and very unlikely of being implemented in a small craft brewery. On the other hand, the use of carbon dioxide as fluidization and gasifying agent would not need a highly stringent purification step nor compression and therefore, it could be a more likely option.

CO_2 gasification has been studied for other feedstocks and published literature show that the use of carbon dioxide as gasification agent (by itself or mixed with air) can improve gasification performance; producing a syngas with a slightly higher H_2 content (around 20% $_{v/v}$) and similar LHV (around 6.0 $MJ/Nm^3_{d.b.}$) can be obtained [34, 35]. Nevertheless, it must be taken into account that CO_2 gasification is a process highly allo-thermal, and as a result of it, the energy balance of the overall process would be utterly unfavourable. Therefore, although CO_2 gasification of BSG could lead in the future to further integration of circular economy approaches in the beer making sector, currently this approach cannot be considered yet as a realistic solution to be implemented in a brewery.

Gas Conditioning Step

Due to gasification process and the physicochemical characteristics of BSG, the presence of small amounts of contaminants in the syngas generated can be expected. Among these contaminants most relevant ones are tar and nitrogen and sulphur species (NH_3, H_2S…). Besides, if the final application of the syngas is its utilization in an engine, the temperature of the syngas must be reduced. To achieve these objectives (remove of contaminants and decrease temperature) different systems can be used which can be classified according to the temperature used in hot and cold cleaning technologies. Cold gas systems have proved reliability and high contaminant removal efficiency so they are the conventional approach on syngas clean-up [36]. Among these systems, wet cold gas clean-up processes are selected due to the fact that they allow for multiple-contaminants removal [37, 38] specially wet scrubbers are high efficiency systems that remove contaminant components of the syngas by spraying water or other liquid through the gas. In the case studied, the liquid selected is water because although it is not the most efficient solvent for the elimination of tars, it allows the removal of other contaminants such as NH_3, H_2S or HCl and it is cheaper.

The energy necessary for these systems depends on the type of scrubber used but it can be assumed that the use of freshwater scrubber can rise the fuel consumption up to 1% [39] so in the case studied, it was considered that the gas conditioning step required 0.7 MWh per year.

Integrated Solution

The costs associated to BSG transportation corresponds to an average of U$16 per tonne of wet BSG transported a distance of 8 km [10]. Therefore local solutions for its elimination are needed in order to minimize costs. The solution presented avoids transportation cost because it will be implemented in the same brewing industry where the waste is produced.

The solution proposes the thermochemical valorisation of BSG by a drying step in a hybrid solar-biomass greenhouse followed by a densification step through a pelletization process and the final conversion by air gasification BSG pellets in a bubbling fluidized bed reactor. For the syngas generated, different applications can be implemented such as generation of heat, electricity or biofuels. The simplest options could be the use of a steam generator that replaces the current diesel boiler or a gas engine to produce electricity for the cooling systems.

In Fig. 2, a simplified diagram with mass and energy balance of the solution is presented. One important first advantage of the proposed system can be easily noticed. The

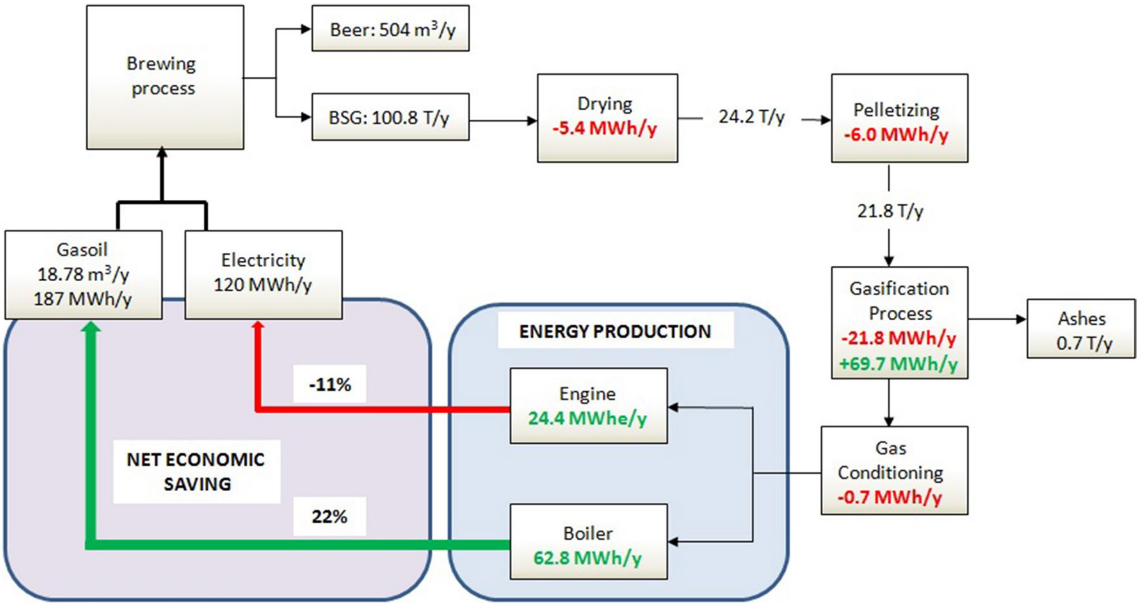


Fig. 2 Scheme of the solution proposed

Table 8 Premises assumed in the study

Process	kWh_{th}/kg
Gasification process produced	3.2
Gasification process consumed	− 1.0
Drying	− 0.05
Pelletizing	− 0.25
Gas conditioning	− 0.032
Net energy available for brewing	1.9

amount of residue is considerably minimized from 100.8 to 0.7 T/y, so BSG gasification not only allows reducing energy external demand but also the remaining waste that must be managed and eventually disposed.

From the brewing process studied, 100.8 tons per year of BSG is obtained with a 76% of moisture. After the drying process selected, the moisture is reduced to 10% so, the dry BSG obtained was 24.2 tons per year and if the densification process is considered, taking into account losses of 10%, the final amount of BSG in pellet form available for their thermochemical valorization by gasification are 21.8 tons per year.

To determine the energy rendered by the gasification of BSG that would be available for the brewing process, some premises that have been aforementioned were adopted. These premises, which are summarized in Table 8, include the gas efficiency of gasification, the energy obtained in the gasification process and the energy requirements for the BSG pre-treatment and syngas conditioning before its final use. So, the net energy obtained from the gasification process that can be implemented in the beer industry is 1.9 kWh_{th}/kg.

Elaborating on the data provided by the craft beer maker La Cibeles (see Table 3), the brewery considered required 187 MWh_{th} per year to generate the necessary steam to be used in the brewing process. If the final solution is meant to use the energy obtained by the gasification of BSG to replace as much as possible the diesel in the steam boiler, the low calorific value of gasoil has to be considered. This value is 35.86 MJ/L compared to the calorific value of the syngas generated, LHVgas = 6 MJ/Nm^3. So, with the gasification of the annual production of BSG, it can be generated 62.8 MWh_{th}. Taking into account that the energy spent in the global process of BSG thermochemical valorization (including drying, pelletizating, and gas conditioning) is of 33.9 MWh_{th}, that means that after BSG gasification process the energy available for the brewing process is 28.9 MWh_{th}/y. Therefore, the amount of fossil fuel required can be reduced around 15%.

On the other hand, if the final solution selected is the generation of electricity, the performance of the engine employed has to be considered. A typical performance for an engine could be 35% so the electrical power that can be supplied by the annual production of BSG would be of 24.4 MWh_e. Unfortunately, this amount is not even high enough to cover the energy requirements of the BSG valorisation process, and therefore, this approach cannot be recommended in this particular case.

Another interesting possibility but a little more complex, is the use of a cogeneration system that produces power and heat through a combined heat and power (CHP) systems. With CHP systems the heat lost during fuel conversion in electricity is recovered in such way that the efficiency achieved can be up to 90%. In the same way other improvements can be implemented in the solution proposed such as the integration of the heat released in the gasification process and gas conditioning step in the brewing process which will reduce the amount of energy necessary for the beer production.

Although BSG valorisation via gasification alone cannot cover the complete energy supply of breweries, the presented solution reduces the utilization of fossil fuels and therefore avoids the associated CO_2 emissions and helps mitigate climate change due to these emissions and can be an incentive to implement 100% renewable energy concepts at breweries.

Economic Analysis

Regarding the economic aspects of the integrated solution here proposed, the main results are summarised in Table 9. In this Table, no personal costs are included, since the operation of the gasification plant would be carried out by the current staff of the brewery.

The estimated CAPEX for the integrated solution proposed, supposing a small gasification plant of 5 kg/h, would

Table 9 Economic assessment of the integrated solution proposed. Adapted from Arena et al. [29]

Concept	CAPEX (Euros)	OPEX* (Euros/y)	Revenues** (Euros/y)
Drying			
Solar air heater	8000		
Fossil fuel boiler	1000	151	
Pelletizing	1400	502	
Gasification process			
Gasification plant (5 kg/h)	110000	1809	
Gas conditioning			
Wet scrubber	2000	58	
Engine	4000	628	2026
Boiler	1000	85	7534

*Taxes included

*Considering 100% energy production through engine or boiler use in non-simultaneous operation be around 123.000 €, which means a significant investment required for a "small brewery". Nevertheless, considering the current prices of the energy for industrial purposes (around 30 €/MWh for natural gas [40], 83 €/MWh for electricity [41] and 120 €/MWh for gasoil [42]), the approach of using the BSG gasification gas in a boiler for heat production is the only option economically feasible, generating a net economic profit of 4.900 €/y, which implies a net economic saving of 22% in the fossil fuels consumption required for the brewing process.

This economic result could be considered initially as disappointed. Nonetheless, two key factors should be noted that improves the economic perspectives of the integrated solution proposed:

(1) Currently, the cost of BSG disposal as residues is only around 30 €/T (which means currently around 3.000 €/y). Therefore, the save of this cost must also be considered indirectly in the economic balance of the process, and increase considerably the net economic profit of the global process up to 8.000 €/y. Moreover, it is expected that the generation of this kind of residues will be severely levied in next future, according to the current guidelines of the European Commission regarding the promotion of circular economy approached in the beer making sector aiming at near-to zero waste generation processes [9].

(2) The economic result of the proposed solution is limited by the scale of the process. Since "La Cibeles" is a small brewery, the amount of BSG generated limit the scale of the gasification plant to be used, and therefore, the global amount of energy produced. For instance, if "La Cibeles" duplicated its beer production capacity twice, the CAPEX investment would be practically the same, but the economic profit of the integrated solution proposed would be more than the double, and consequently, the amortization period of the CAPEX would be reduce significantly.

With these considerations, the proposed solution for BSG thermochemical valorisation through gasification presents interesting perspectives from both energy and economic point of views.

Conclusions

Following circular economy thinking, thermal valorisation of BSG via gasification has been analysed as an alternative way to current waste management practices in small breweries, which mostly rely on the use of BSG for animal feeding. To that aim the physicochemical characterization of the residue has been carried out, available data of BSG gasification have been used and the real thermal and power necessities of a craft brewery have been taken into account.

Based on the results presented, if BSG gasification were implemented in the selected craft beer case for heat generation, the net energy that could be implemented in the brewing process would be of 28.9 MWh_{th}/y, which implies a net economic saving of 22% in the fossil fuels consumption required for the brewing process.

According to the results obtained, the use of the BSG gasification gas for electricity production is not profitable energetic nor economically in the case studied of "La Cibeles", mainly due to the fact that "La Cibeles" is a small brewery, and it cannot generate enough amount of BSG.

In the same way, due to the small scale of "La Cibeles", the economic results of the solution proposed may seem initially a little disappointing. Nevertheless, taking into account that the final volume of the residue to be disposed would be greatly minimised, which implies significant saves in the current and future costs according to the CE guidelines, and that the revenues will increase considerably if "La Cibeles" increased its beer capacity production, the solution proposed is proved as a feasible option to be seriously considered for further applications, especially in the context of circular economy and near-to zero waste generation processes.

Acknowledgements The authors wish to thank the Regional Government of Madrid for its financial support through the RETOPROSOST Project (P2013/MAE-2907). We also thank La Cibeles, S. L. for providing the data for this study.

References

1. The Brewers of Europe: The Contribution made by Beer to the European Economy. In. Region Plan Policy Research and EY (2013)
2. Kawa, A., Luczyk, I.: CSR in supply chains of brewing industry. In: Golinska, P., Kawa, A. (eds.) Technology Management for Sustainable Production and Logistics. EcoProduction, pp. 97–118. Springer, Berlin (2015)
3. Kerby, C., Vriesekoop, F.: An overview of the utilization of brewery by-products as generated by british craft breweries. Beverages **3**(24), 1–12 (2017). https://doi.org/10.3390/beverages3020024
4. El economista: la producción de cervezas artesanales en España se disparó un 36% en 2017. https://www.eleconomista.es/distribucion/noticias/9158845/05/18/Economia-Consumo-La-produccion-de-cervezas-artesanales-se-dispara-en-Espana-un-36-en-2017.html. (2018). Accessed Jan 2019
5. Olajire, A.A.: The brewing industry and environmental challenges. J. Clean. Prod. (2012). https://doi.org/10.1016/j.jclepro.2012.03.003
6. Agency, E.E.: Circular economy in Europe. Developing the Knowledge Base. In., vol. EEA Report No 2/2016, p. 42. EEA, Luxembourg (2016)
7. European Commission: The opportunities to business of improving resource efficiency. Final Report. In: AMEC Environment & Infrastructure and Bio Intelligence Service (2013)
8. Association, B.: Solid Waste Reduction Manual. In: Brewers Association,

9. European Commission: The role of waste-to-energy in the circular economy. In: (vol. COM, p. 11). European Commission (2017)
10. Mussatto, S.I.: Brewer's spent grain: a valuable feedstock for industrial applications. J. Sci. Food Agric. **94**(7), 1264–1275 (2014). https://doi.org/10.1002/jsfa.6486
11. dos Santos Mathias, T.R., de Mello, P.P.M., Sérvulo, E.F.C.: Solid wastes in brewing process: a review. J. Brew. Distill **5**(1), 1–19 (2014). https://doi.org/10.5897/jbd2014.0043
12. Weger, A., Jung, R., Stenzel, F., Hornung, A.: Optimized energetic usage of brewers' spent grains. Chem. Eng. Technol. **40**(2), 306–312 (2017). https://doi.org/10.1002/ceat.201600186
13. Mejores técnicas disponibles en el sector cervecero. In: AINIA-Instituto Tecnológico Agroalimentario, p. 119
14. Mussatto, S.I., Dragone, G., Roberto, I.C.: Brewers' spent grain: generation, characteristics and potential applications. J. Cereal Sci. **43**(1), 1–14 (2006). https://doi.org/10.1016/j.jcs.2005.06.001
15. Pérez, V., Murillo, J.M., Bados, R., Esteban, L.S., Ramos, R., Sánchez, J.M.: Preparation and gasification of brewers' spent grains. In: 5th International Conference on Sustainable Solid Waste, Athens, 2017
16. Phyllis2. Database for biomass and waste. ECN. Accessed 2018
17. Torreiro, Y., Ortiz, I., Molina, G., Maroño, M., Pérez, V., Murillo, J.M., Ramos, R., Fernández, M., García, S., Sánchez, J.M.: Thermochemical assessment of *Nicotiana glauca*, *Panicum virgatum* and *Elytrigia elongata* as fuels for energy recovery through gasification. Fuel **225**, 71–79 (2018). https://doi.org/10.1016/j.fuel.2018.03.149
18. Jenkins, B.M., Baxter, L.L., Miles, T.R., Miles, T.R.: Combustion properties of biomass. Fuel Process. Technol. **54**(1), 17–46 (1998). https://doi.org/10.1016/S0378-3820(97)00059-3
19. Thomas, K.R., Rahman, P.K.S.M.: Brewery wastes. Strategies for sustainability. A review. ASP Appl Biol **8**, 147–153 (2006)
20. Stelte, W., Holm, J.K., Sanadi, A.R., Barsberg, Sr, Ahrenfeldt, J., Henriksen, U.B.: Fuel pellets from biomass: the importance of the pelletizing pressure and its dependency on the processing conditions. Fuel **90**(11), 3285–3290 (2011)
21. Stelte, W., Clemons, C., Holm, J.K., Sanadi, A.R., Ahrenfeldt, J., Shang, L., Henriksen, U.B.: Pelletizing properties of torrefied spruce. Biomass Bioenerg. **35**(11), 4690–4698 (2011)
22. Zafar, S.: Biomass Pelletization Process. (2018)
23. Pascual, L.S.E.: Fuel preparation. Paper presented at the summer school: advanced concepts and process schemes for CO2 free fluidised and entrained bed co-gasification of coals, Madrid, 3–6 July
24. Pirraglia, A., Gonzalez, R., Saloni, D.: Wood pellets feasibility. Bioresource **5**(4), 2374–2390 (2010)
25. Higman, C., Burgt, M.V.D.: Gasification, 2nd edn. Gulf Professional Publishing, Amsterdam (2008)
26. Sikarwar, V.S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M.Z., Shah, N., Anthony, E.J., Fennell, P.S.: An overview of advances in biomass gasification. Energy Environ. Sci. **9**(10), 2939–2977 (2016). https://doi.org/10.1039/C6EE00935B
27. Narváez, I., Orío, A., Aznar, M.P., Corella, J.: Biomass gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Ind. Eng. Chem. Res. **35**(7), 2110–2120 (1996). https://doi.org/10.1021/ie9507540
28. Toledo, J.M., Corella, J., Molina, G.: Catalytic hot gas cleaning with monoliths in biomass gasification in fluidized beds. 4. Performance of an advanced, second-generation, two-layers-based monolithic reactor. Ind. Eng. Chem. Res. **45**(4), 1389–1396 (2006)
29. Arena, U., Di Gregorio, F., Santonastasi, M.: A techno-economic comparison between two design configurations for a small scale biomass-to-energy gasification based system. Chem. Eng. J. **162**, 580–590 (2010)
30. Sanz, A., Corella, J.: Modeling circulating fluidized bed biomass gasifiers Results from a pseudo-rigorous 1-dimensional model for stationary state. Fuel Process. Technol. **87**(3), 247–258 (2006). https://doi.org/10.1016/j.fuproc.2005.08.003
31. Nikoo, M.B., Mahinpey, N.: Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS. Biomass Bioenerg. **32**, 1245 (2008)
32. Sahoo, A., Ram, D.K.: Gasifier performance and energy analysis for fluidized bed gasification of sugarcane bagasse. Energy **90**, 1420–1425 (2015). https://doi.org/10.1016/j.energy.2015.06.096
33. The utilisation of brewery waste (1923) https://doi.org/10.1002/j.2050-0416.1923.tb02583.x.
34. Karatas, H., Olgun, H., Akgun, F.: Experimental results of gasification of waste tire with air&CO2, air & steam and steam in a bubbling fluidized bed gasifier. Fuel Process. Technol. **102**, 166–174 (2012). https://doi.org/10.1016/j.fuproc.2012.04.013
35. Garcia, L., Salvador, M.L., Arauzo, J., Bilbao, R.: CO_2 as a gasifying agent for gas production from pine sawdust at low temperatures using a Ni/Al coprecipitated catalyst. Fuel Process. Technol. **69**(2), 157–174 (2001). https://doi.org/10.1016/S0378-3820(00)00138-7
36. Abdoulmoumine, N., Adhikari, S., Kulkarni, A., Chattanathan, S.: A review on biomass gasification syngas cleanup. Appl. Energ. **155**, 294–307 (2015). https://doi.org/10.1016/j.apenergy.2015.05.095
37. Woolcock, P.J., Brown, R.C.: A review of cleaning technologies for biomass-derived syngas. Biomass Bioenerg. **52**, 54–84 (2013). https://doi.org/10.1016/j.biombioe.2013.02.036
38. Balas, M., Lisy, M., Skala, Z., Pospisil, J.: Wet scrubber for cleaning of syngas from biomass gasification. In: Advances in Environmental Sciences, Development and Chemistry, Santorini Island, Greece, July 17–21, 2014, pp. 195–201 (2014)
39. Boer, E.D., Hoen, M.T.: Scrubbers—an economic and ecological assessment. In: Delft, C. (ed.). p. 45, NABU, Delft (2015)
40. Eurostat: Estadísticas de los precios del gas natural. (2018). https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics/es#Precios_del_gas_natural_para_consumidores_no_dom.C3.A9sticos. Accessed Jan 2019
41. Ministerio de Industria, Comercio y Turismo: Precio neto de la electricidad para uso doméstico y uso industrial. (2018). https://www.mincotur.gob.es/es-ES/IndicadoresyEstadisticas/DatosEstadisticos/IV.%20Energ%C3%ADa%20y%20emisiones/IV_12.pdf. Accessed Jan 2019
42. Ministerio de Industria, Comercio y Turismo: EVOLUCIÓN PRECIOS DEL GASÓLEO. (2019). http://www.cetm.es/principal/carburantes/gasoleos/datos.asp. Accessed Jan 2019