Energy 223 (2021) 120039

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

State-of-the-art of small-scale biomass gasification systems: An extensive and unique monitoring review

Francesco Patuzzi [a, *], Daniele Basso [a], Stergios Vakalis [b], Daniele Antolini [a], Stefano Piazzi [a], Vittoria Benedetti [a], Eleonora Cordioli [a], Marco Baratieri [a]

[a] Faculty of Science and Technology, Free University of Bolzano, Piazza Università 5, 39100, Bolzano, Italy
[b] Department of Environment, University of the Aegean, University Hill, Xenia Building A, 81100, Mytilene, Greece

ARTICLE INFO

Article history:
Received 28 November 2020
Received in revised form
26 January 2021
Accepted 31 January 2021
Available online 2 February 2021

Keywords:
Biomass
Gasification
Small-scale CHP
Char

ABSTRACT

During the last few years, there has been an increasing interest in small-scale biomass gasification in Central and Northern Europe. Since 2011, almost fifty small-scale biomass gasification plants have been authorized and built in the South Tyrolean region (Italy), and most of them are currently operating. Within this framework, an extensive survey was performed by means of questionnaires to the plant owners for assessing the biomass and char flows in the region. Moreover, a comprehensive monitoring campaign was carried out onsite on representative plants of almost all the available operating technologies. For each of the monitored plants, the feedstock and the gasification products were characterized and their fluxes quantified, leading to energy and mass balances. This allowed collecting an extended set of data and drawing up a unique overview of the reference values for the ranges of operation of small-scale biomass gasification systems currently available in the European market, in terms of equivalence ratio, dry gas composition and heating value, specific electricity production, and conversion efficiencies. Moreover, samples of chars were deeply characterized, providing an insight into possible utilization pathways for the valorization of this by-product that is currently disposed of, representing an economical and environmental burden.

1. Introduction

Several novel processes and technologies that aim to advance the thermochemical conversion of biomass and the production of sustainable biofuels and bioproducts are currently under development. Due to the gradual commercialization of such technologies, biomass has become a very interesting and promising renewable resource [1] for the design of novel energy pathways [2] and the extraction of valuable molecules [3] and materials from it [4]. Energy from biomass, also referred to as bioenergy, is defined as the energy recovered from non-fossilized organic matter [5]. Lignocellulosic (woody) biomass is the largest biomass energy resource worldwide. At the same time, other biomass resources are also significant and with high potential, i.e. biomass from agriculture, forest maintenance [6], and the organic fraction of municipal solid waste (food waste, kitchen waste and garden waste) [7]. Because of its intrinsic chemical complexity and richness, biomass can be considered an important resource not only for energy production but also for polygeneration, this being defined as the production of at least three different products, which in case of thermochemical conversion such as gasification, are typically heat, electricity, and valuable by-products or biofuels [8,9]. Among the available thermochemical biomass conversion processes, biomass gasification has been gaining a lot of attention due to the very promising potential for polygeneration and production of additional valuable streams on top of the standard CHP (combined heat and power) [10–12]. Interestingly, small-scale woody biomass gasification systems have encountered a noticeable diffusion in Europe, mostly in Germany and in Northern Italy, representing a great opportunity to move towards a comprehensive study of the process, the technology behind it, and its potentialities [13].

In particular, this study focuses on South Tyrol, a mountain region located in the North-Est of Italy and covered by forest for more than 45% of its extent [14]. Because of the abundancy of woody biomass coming from forest maintenance activities and encouraged by the increased tariffs for renewable energy producers, the

* Corresponding author.
E-mail address: francesco.patuzzi@unibz.it (F. Patuzzi).

https://doi.org/10.1016/j.energy.2021.120039

application of woody biomass gasification technology has had a rapid increase in South Tyrol during the last years. Furthermore, the level of development of the gasification technology, that has led to high performance gasifiers, has made the investment on this type of technology more and more appealing [15]. In a previous work by Patuzzi et al. [16], four representative gasification technologies of the South Tyrolean region were investigated, monitored and assessed for their performance. The authors concluded that although the distribution between electrical and thermal efficiency was not identical among the different technologies, the overall CHP efficiency for all four gasification plants was similar and slightly above 70%. The analysis of the energy balances highlighted the significant impact of the heat losses and identified the cases for which the high temperature of the discharged heat amplified the issue [17].

Until recently, the status quo in respect to standard small-scale gasification solutions was considered to be (primarily) downdraft gasifiers with cold gas filtering. However, newer technological developments brought to a competitive level also updraft (or updraft-like) gasifiers, double-fired gasifiers, floating bed gasifiers, and gasifiers that utilize hot gas filtering, thus increasing the number of available technologies to about ten. These technologies started to produce a different spectrum of by-products in comparison to the conventional downdraft gasifiers. In addition, the scale of operation started to rise significantly, from around 180 kW_{el} up to 1 MW_{el} [18], along with the corresponding total output volume of by-products, such as tar and char. The analysis of the total flows of these materials is necessary in order to possibly develop a more sustainable and holistic management of them. In fact, the identification of the amounts of by-products is a required step for designing a strategy in order to further utilize them as raw materials or to safely dispose of them without affecting the environment. Especially char, the solid carbonaceous residue, shows many similarities with activated carbon (AC) and thus could hypothetically replace AC in different fields of application [19]. Due to its high carbon content and well-developed porosity, char could be used not only for combustion [20,21], but also for gas and dye adsorption [22–24], catalyst preparation [25,26], tar cracking [27,28], and soil fertilization [29]. Eventually, char could be considered as a valuable resource leading to a remarkable reduction of the economic and energetic costs associated to its disposal. Therefore, it is crucial to analyze its characteristics thoroughly and to understand the relationship with the gasification technology that produced it.

Within this context, an in-deep investigation on all the technologies installed and operating in South Tyrol was carried out through a monitoring campaign performed on at least one gasification plant for each technology, followed by the calculation of both mass and energy balances. Moreover, through this work, it was possible to complete the census of all the small-scale gasification plants installed in this region, along with their characterization in terms of technology, type of gasifier, nominal electrical power, and installation year.

The presentation of novel small-scale biomass gasifiers along with their monitoring, and the complete analysis of these novel technologies represent a unique and challenging endeavor. In addition, the monitoring campaign was developed in order to consider the gasifiers as polygeneration technologies, analyzing their performance with a holistic approach, and therefore coupling the standard analyses with the sampling and analysis of the gasification by-products. In particular, the different collected chars were deeply characterized in order to evaluate their possible applicability as soil improvers with respect to the current Italian legislation. This approach was designed for covering the research gaps existing in the research on gasification processes and the corresponding industrial applications up to the present. Thus, the scope of the study is to present the results from the monitoring activities and the comparative performance analysis of the different gasification technologies. An additional attribute of this work is that the monitoring was implemented in accordance with the Recommendation CTI 13 (which is the only existing set of guidelines for such measurements), and therefore this study could be considered as a reference document for assisting other relevant future studies.

2. Materials and methods

2.1. Mapping small-scale gasification plants

This activity consisted in updating the map of the small-scale gasification plants installed in South Tyrol. Mapping was performed using the databases and publications made available by the Italian Gestore Servizi Energetici (GSE) and Atlaimpianti [30]. The database, that comprises all the production data regarding plants that produce both heat and power in Italy, has been integrated with data from the Office of Air and Noise (Ufficio Aria e Rumore) of the Autonomous Province of Bolzano [31]. The gasifiers under analysis were categorized by manufacturing company and authorization year. Furthermore, pieces of information on plant localization, gasification technology, type of gasifier, type and physical and chemical characteristics of biomass, feeding system, gasifier agent, gas cleaning and conditioning system, and type of engine for electricity production, were gathered.

The different technologies installed in South Tyrol are listed in alphabetical order in Table 1, together with some basic information like reactor typology and biomass type. Further details are not provided in order to prevent the identification of the correspondence between technologies and adopted labels. For non-disclosure reasons, in fact, the different technologies are labelled in the rest of the manuscript with capital letters and following a different non-specific order.

2.2. Assessment of biomass and char flows in the region

Once identified the location of the plants, questionnaires were sent to the plant owners. This was done, on the one side, to corroborate the mapping of the plants and, on the other side, with the additional aim of collecting quantitative information about the flows of woody biomass used for energy purposes in gasification plants in South Tyrol and of solid residues (char) produced in these plants. In addition, the questionnaires helped understanding some other qualitative aspects, such as the current procedures for the disposal of char, the possible treatment methods and the final destination of the solid residue. Although the questionnaires were in some cases autonomously filled in by the plant owners, in most of the cases the filling was performed through interviews – conducted telephonically or, preferably, in presence during onsite visit to the plants.

2.3. On site plant monitoring: sampling and performance evaluation

The bases for the monitoring activity were set through surveys performed on selected plants. The selection of the plants was done considering two main aspects: a) the plant had to be representative of the most diffused technologies and b) its owner, after being contacted and informed of the purpose of the study, had to show interest in the participation to the survey and be willing to give access to the plant in order to perform the required measurements and analyses. The involvement and agreement with the owners were in fact basic requirements for the success of the monitoring

Table 1
Small-scale gasification technologies installed in South Tyrol, listed in alphabetical order with some basic information about reactor typology and biomass type.

Technology provider	Reactor type	Fuel	Ref.
Burkhardt GmbH	rising co-current, stationary fluidized bed	pellet	[32,33]
Entrade Energiesysteme AG	downdraft, fixed bed	pellet	[34,35]
Hans Gräbner	downdraft, fixed bed	wood chips	–
Holzenergie Wegscheid GmbH	downdraft, fixed bed	wood chips	[36]
Kuntschar Energieerzeugung GmbH	downdraft, fixed bed	wood chips	[37]
Spanner Re^2 GmbH	downdraft, fixed bed	wood chips	[38,39]
Stadtwerke Rosenheim GmbH	double stage, fluidized bed	wood chips	[40]
Syncraft Engineering GmbH	double stage, floating fixed bed	wood chips	[41,42]
Urbas Maschinenfabrik GmbH	downdraft, fixed bed	wood chips	[43,44]
Wubi GmbH	downdraft, fixed bed	wood chips	–
Xylogas & EAF	downdraft, fixed bed	wood chips	–

activity itself. With their collaboration, the monitoring activities were planned. It this worth highlighting that the monitoring was actually performed as third-party due diligence activity, without involving the technology providers and thus avoiding any kind of conflict of interest – the owner were interested in evaluating the performance of their plants during actual operation and no particular precautions were kept to ensure the fulfilling of nominal conditions. All the measurements of the mass and energy fluxes were performed on a minimum basis of 5–6 h of continuous operation, through on-site non-invasive measurements and samplings. In particular, woody biomass entering the reactor, air flow (i.e. the gasifying agent flux), producer gas and residual char were considered for the calculation of the mass balance. Both the woody biomass and the char amounts were measured with a balance and, when available, the data were compared to those measured by the control system integrated in the plant. The airflow was calculated measuring its velocity through a Pitot tube installed in a pipe of known dimensions connected to the air input. Finally, the producer gas flow rate was determined knowing the gas composition and the input air flow rate and assuming negligible the nitrogen content in the fuel. A detailed description of the methodologies applied for carrying out both mass and energy balances can be found in previous studies by Patuzzi et al. [45].

The overall CHP efficiency of each monitored plant was calculated as the sum of the electrical and thermal efficiencies (equation (1)). The electrical and thermal efficiencies were evaluated according to equations (2) and (3).

$$\eta_{tot} = \eta_{el} + \eta_{th} \quad (1)$$

$$\eta_{el} = (P_{el} - P_{aux}) \Big/ \left(\dot{m}_{biomass} \cdot LHV_{biomass} + \dot{m}_{secondary-fuel} \cdot LHV_{secondary-fuel} \right) \quad (2)$$

$$\eta_{th} = P_{th} \Big/ \left(\dot{m}_{biomass} \cdot LHV_{biomass} + \dot{m}_{secondary-fuel} \cdot LHV_{secondary-fuel} \right) \quad (3)$$

In equations (2) and (3) P_{el} is the electric power in kW, P_{aux} is the electric self-consumption of the auxiliary equipment in kW, P_{th} is the thermal power in kW, $\dot{m}_{biomass}$ is the dry biomass flow rate in kg/s. $LHV_{biomass}$ is the lower heating value of the input biomass in kJ/kg on dry basis, evaluated as described in the following section. For sake of completeness, the possible contribution of a secondary fuel is also taken into account in the equations, although this is the case only for one of the considered technologies.

2.4. Feedstock and gasification products and by-products characterization

The woody biomass used as feedstock in the gasifiers and the char collected during the monitoring activities were characterized and their flow rates quantified. Dry mass flow rates of both woody biomass and chars were calculated, after having determined their moisture content according to the UNI EN ISO 18134–1:2015 standard. Ash content (UNI EN ISO 18122:2016) elemental composition (UNI EN ISO 16948:2015) and heating value (UNI EN ISO 18125:2018) were also determined for each sample. In addition, in order to evaluate the suitability of char as soil improver, char samples were characterized in terms of metals content, dioxins (DX; method: EPA 1613B 1994), polychlorobiphenyls (PCB; method: EPA 1668C 2010), and polycyclic aromatic hydrocarbons (PAH; method: MI-03 rev. 13 2016).

The sampled producer gas, after being flown through a series of impinger bottles filled with isopropanol for the removal of the condensable fraction in accordance to the technical specification UNI CEN/TS 15439, was analyzed on-line by means of a portable gas chromatograph (microGC 490, Agilent), equipped with two columns, a Molsieve column able to detect H_2, O_2, N_2, CH_4 and CO, and a Plot-U column able to detect CO_2, C_2H_4, C_2H_6 and C_3H_6/C_3H_8 (C_3's). Before each monitoring, the microGC device was calibrated using a calibration mixture. For each species, a 5-points calibration curve was obtained diluting in nitrogen, at different levels, the calibration mixture by means of a gas mixer (Zephyr GasMix, Alytech).

3. Results and discussion

3.1. Assessment of the South Tyrol case study through questionnaires collection

A total of 17 questionnaires were collected, as depicted in Fig. 1, which shows – for each technology installed in South Tyrol – the number of collected questionnaires compared to the number of installed plants. The graph anticipates some of the figures that will be discussed more in detail in the next subsection. In particular, it is possible to observe a larger diffusion of one technology (identified with letter A) with respect to the other technologies; indeed 59.6% of all the plants installed in South Tyrol belong to technology A (54.8% considering only the plants in operation). This technology was the first facing the market of small-scale gasification systems in South Tyrol back in 2011 and it is also the only one that, as of 2019, includes plants that are not in operation anymore.

Because of this unbalanced diffusion of the different technologies, the number of collected questionnaires appears to be satisfactorily representative – despite an overall covering rate of only 40.5% of all the plants in operation (17 questionnaires out of 42 plants in operation), the covering rate is 100% for six technologies

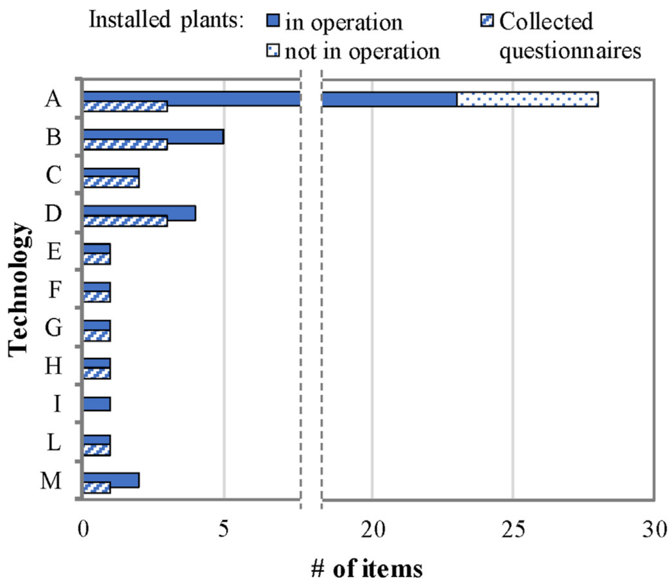

Fig. 1. Number of collected questionnaires compared to the number of installed plants for each gasification technology installed in South Tyrol.

and ranges from 50% to 75% for other three. Only for one technology (the one identified with letter I) no questionnaires were collected; nonetheless, this did not particularly affect the survey since this technology is represented by a single manually loaded plant, not actually representative of the present state of the art of small-scale gasification systems.

3.1.1. Small-scale technologies: diffusion and development

Gasification plant projects have started to be presented for authorization in 2008, but only in 2012 the first plants were authorized and started to work. At present, the number of authorizations requested to the Autonomous Province of Bolzano (IT) is almost twice the number of the plants that are running, meaning that almost half of the projects have been abandoned or not authorized. Fig. 2 presents the gasification plants in South Tyrol in operation in 2017, along with the year of their authorization. As previously anticipated, it is clear that technology A – also considering that the few plants installed but currently not in operation belong to this technology – was the first being able to tackle the market of small-scale gasification systems, ensuring its position and a higher and widespread diffusion thanks to a low number of competitors.

As shown in Fig. 2, a peak of authorization acts in the Province has been reported for the years 2012–2014. This trend can be explained by the fact that in 2012 the Italian Government published the Ministerial Decree July 06, 2012 (*Incentives for energy from renewable, non-photovoltaic electricity sources*), which established economic incentives to produce renewable electric energy from non-PV technologies. The detailed financial mechanisms, by means of feed-in tariffs, tax exemptions and green certificates, were described in a previous work [46], but they are herein recalled. Solid-biomass-based plants for electricity production had direct access (i.e., with simplified procedures) to particularly favorable all-inclusive feed-in tariffs when their nominal size did not exceed the threshold of 200 kW_{el}. Plants of nominal size between 200 kW_{el} and 1 MW_{el} could also have access to the all-inclusive feed-in tariffs through the registration on booking logs with specific quotas for the total installed power and prioritization criteria. This mechanism, which was introduced as a system of control and governance of mounted volumes and their overall spending, has led to a more widespread diffusion of plants with nominal size lower than 200 kW_{el}, although there are also examples of larger plants. The feed-in tariff was composed by a plant-size- and feedstock-quality-dependent base tariff and additional cumulative premium rates for low levels of emissions and high cogeneration efficiencies. The highest base tariff, ranging in the case of small-scale plants between 229 €/MWh and 257 €/MWh depending on the feedstock (virgin biomass or woody by-products, respectively), was set in 2013. Starting from that, the base tariff has decreased by 2% each year. It is worth mentioning that, in the years before, the feed-in tariff was even higher, reaching a value of 280 €/MWh. Such high incentives strongly supported private investments and, as demonstrated by the high number of plants already authorized in 2012, boosted the development of a technology that at that time was not yet established on the market, ensuring short payback periods (in the order of 3–5 years depending on the cases). Although most installations are virtuous examples, it must be observed that few of the plants installed in the first years of subsidization were optimized for maximizing only the electricity production, treating the heat stream as a by-product rather than as an energy source to be valorized. Such an approach is clearly sustainable only with high feed-in tariffs. Indeed, today, as demonstrated by the continuously decreasing number of installed plants

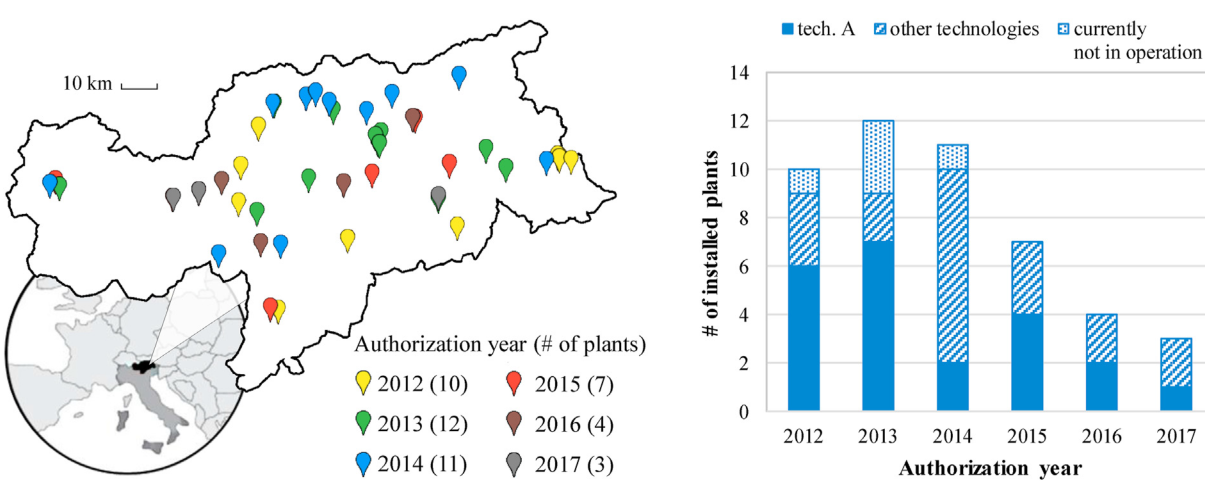

Fig. 2. Small-scale gasification plants operating in South Tyrol and evolution of the authorizations.

after 2013, small-scale biomass gasification systems can be profitable only in peculiar cases. A combination of concurrent conditions should be satisfied, e.g. the feedstock is available at a sufficiently low cost, the plant is dimensioned on the heat demand, and the electricity – even better if self-consumed – is only an additional benefit.

After 2013 the interest on investing in the gasification technology continuously decreased because of both the decrease of the incentives and the financial impacts of the global economic crisis. As a result of the described context, at the time of the study, 47 gasification plants have been reported to be installed and 42 in operation. Among the operating gasification plants, 8 main technologies were identified for the monitoring campaign. Although these technologies present several similarities, they also have significant differences. In fact, the gasification technologies are composed by analogous parts and elements, as regards for instance the feeding of the feedstock or the gas cleaning units, that have become common standards in the modern design of small-scale gasifiers. The most used feeding system consists of screws/augers and sometimes pneumatic pumps. Moreover, all the systems considered have some level of automation and most of them are already fully automated. As regards the quality of the woody feedstocks, that is currently guaranteed by (extensively) drying the biomass or by directly using dried high-quality biomass, while the input air is commonly pre-heated in order to accomplish higher overall gasification performances. Regarding engines, two options are generally used: spark ignition and compression ignition engines [47]. Both solutions present critical and favorable features. Spark ignition (SI) engines provide an easy implementation of producer gas combustion since the combustion process is controlled by the spark plug. On the other hand, when using low energy density fuels, SI engines are subjected to a critical power derating (up to 40%) due to the typically low compression ratios [47,48]. Compression ignition (CI) engines ensure higher compression ratios with respect to SI ones, thus reducing the power derating up to 20% [47]. Unfortunately, the need to co-combust two different fuels – namely diesel and producer gas – and the associated challenging dual-fuel combustion mode has limited the diffusion of this technology [48,49]. Moreover, critical environmental issues (such as the particulate matter emissions) are currently related to the use of diesel combustion technologies [50]. In such a framework, an interesting solution is represented by the so-called modified diesel engine. In this kind of system, a CI engine is equipped with a spark plug, providing better emissions control and reduction [48,51]. Due to their technical feasibility, SI engines are currently the most spread solution on the market and represent the operators' first choice. However, modified diesel engines may represent a valid substitute to ensure both easy implementation as well as high energy conversion performances.

Some characteristics were identified as unique and particular for each specific technology. For example, the "floating fixed-bed" reactor is a peculiar technology that takes advantage of the compaction forces; the rising co-current reactor was designed to create a vortex above the combustion zone and a stabilized semi-fluidized char bed that resembles the concept of the spouted bed. Moreover, some technologies recirculate fractions of gas or char back into the reactor. Finally, one of the technologies was designed to perform a first biomass carbonization stage prior to entering the gasifier.

3.1.2. Wood and char flows in South Tyrol

Based on the information collected through the questionnaires and the total number of installed modules for each technology, the total flows of biomass and char in the region were estimated. For those plants whose owners did not answer to the questionnaire, average biomass consumption and char production values were assumed, based on the data available for the specific technology/module. According to this estimation, each year 49.16×10^6 kg of woody biomass is used in South Tyrol for energy purposes in the installed gasification systems. The amount of char produced each year accounts for 1.18×10^6 kg, which is disposed of with an average cost of 15 c€/kg.

An aggregate overview of the most significant data obtained from the questionnaires is shown in Fig. 3. Most of the biomass used in the gasification plants participating to the survey comes from South Tyrol, being directly produced by the plant owners or acquired from local producers. A share of 40% is acquired from other regions, mainly foreign countries such as Austria, Germany, Slovenia, or Poland. This significant share is undoubtedly correlated to the fact that 28% of the wood used in the plants participating to the census is in the form of pellets, typically acquired from outside the region. Actually, 4 of the 17 received questionnaires come from plants operated with pellets as fuel and this could negatively impact the representativeness of these figures, being this share higher than the share of plants operated with pellets with respect to the total number of plants. More significant is the fact that, without considering the plants fed with pellets, almost half of the biomass is purchased or gathered as roundwood and locally processed to produce chips. It is worth specifying that wood chips and roundwood are usually obtained from forest maintenance and sawmill processing residues, and come almost entirely from South Tyrol, except for a very small part purchased in Austria and Slovenia. The pellets, on the other hand, come almost entirely from Austria, but in small quantities they are also purchased from Poland or directly from South Tyrol.

The data about the characteristics of the chipped biomass reported in Fig. 3 show that most of the plants utilize small size (G30-G50) or medium size (G50-G100) wood chips, although one of the most widespread technologies after technology A is optimized for bigger size wood chips (G100-G150), as denoted by a share of 12% for this size range. In general, each technology is optimized for a certain range of wood chips size and too small or too large pieces always represent a problem for the smooth operation of the reactors; the content of fines cannot normally exceed 20% otherwise they could pack inside the reactor, preventing its regular operation and clogging it. Some technologies appear to be more sensitive than others, and their plant owners are forced to use a screening system that essentially eliminates this fraction.

The moisture content of the biomass fed to the reactor cannot typically exceed 10% for any technology. As anticipated, some plant owners satisfy this quality requirement by purchasing already dried biomass at higher costs, others preferred to install their own external dryer; some technologies included an initial drying stage in the main unit. For this reason, the moisture content of the purchased feedstock can be greatly variable, ranging from 5 to 10% for the dried wood chips and the pellets, up to 50–55% for the roundwood deposited in open areas.

According to the questionnaires, a significant variability can be observed in the purchasing price of biomass. That is determined by various factors such as the type and quality of the supplied biomass (roundwood or wood chips, dried or not, screened or not, etc.), the logistic associated to the delivery (more or less accessible areas, on delivery routes to other customers, etc.), and obviously the size of the plant and therefore the quantities purchased. In terms of average cost, by type of biomass, some representative figures are: 4.9 c€/kg for roundwood, 9.4 c€/kg for wood chips and 22.0 c€/kg for pellets. As for the final destination of char, 31% of it is delivered outside the Province, while 69% is disposed of by specialized companies directly in South Tyrol.

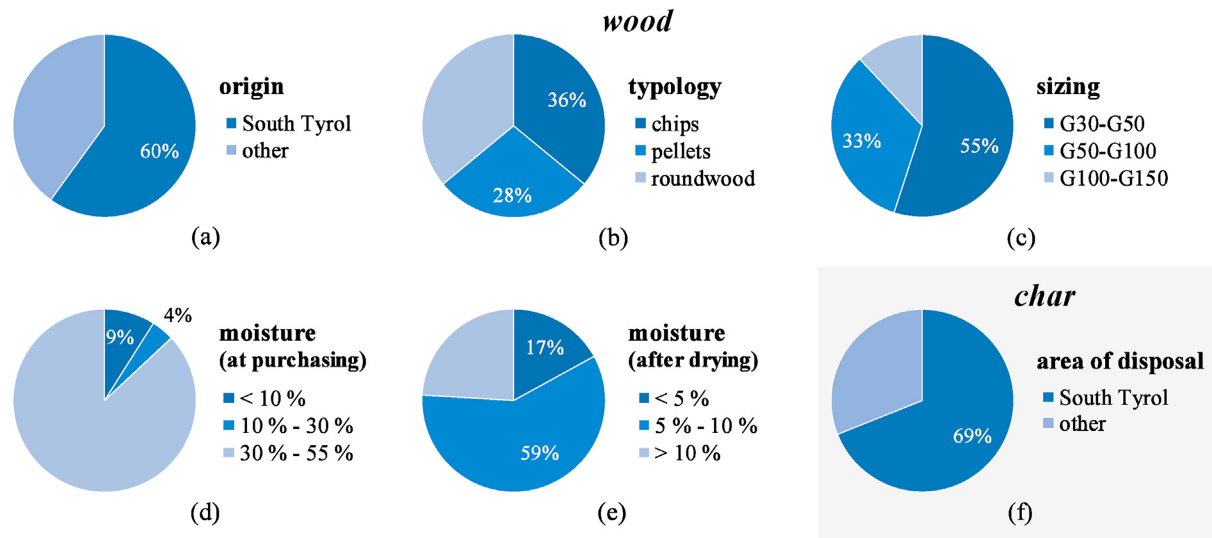

Fig. 3. Aggregate results of the collected questionnaires about (a) origin and (b–e) characteristics of the woody biomass used for energy purposes in the gasification plants of South Tyrol and (f) area of disposal of the produced char.

3.2. Gasification inputs and outputs analyses

The results of the chemical and physical characterizations of both feedstocks and chars collected during the monitoring campaign are shown in Table 2.

As far as biomass is concerned, humidity is always below 12% and the ash content is below 1%. Indeed, a high ash content would be problematic for the undisrupted operation of small-scale gasifiers [52]. The literature findings are in good agreement with the actual operation of small-scale gasifiers in which only high-quality biomass is used as feedstock. This can also be appreciated when considering that the LHV of biomass ranges between 15.9 and 18.1 MJ/kg, with a standard deviation of only 0.67 MJ/kg. Most gasification producers claim that, with small modifications, the gasifiers will eventually be able to operate with agricultural waste instead of high-quality biomass. However, this supposition has not been confirmed yet, and low moisture and low ash contents are still crucial parameters for the undisrupted operation of such reactors, which can be more or less sensitive to the amount of ash in the feedstock depending on their specific configuration and the possibility of easily extracting any ash agglomerate formed during the process. Furthermore, the data indicate that although the chemical and physical characteristics of biomass are similar for all the technologies, bigger differences can be appreciated for the chars. This inference can be confirmed considering both carbon content and LHV of chars. In fact, the carbon content varies among the chars passing from a very high carbon content for the char produced by technology F (91.59%) to a very low carbon content in the char produced by technology C (48.03%), which also shows the highest hydrogen content (0.89%). The char from technology C is quite different from the other chars, although the biomass used as feedstock has a composition very similar to that of other technologies here considered. This is ascribed to a peculiar gasifier configuration in which the char, after being filtered out from the producer gas by means of a cyclone, is redirected into the main reactor, thus increasing the carbon conversion.

The results show also that, although the variations of the LHV of the biomass feedstocks are modest, bigger differences on the LHV of chars can be observed. In fact, LHV of char ranges between 14.3 and 30.8 MJ/kg, with a standard deviation of 4.6 MJ/kg, indicating that

Table 2
Chemical and physical characterizations of woody biomasses and chars.

Technology		Ash	C	H	N	S	O[a]	LHV	Moisture	Surface area
				[%wt_{dry}]				[MJ/kg_{dry}]	[%wt_{ar}]	[m^2/g]
A	Biomass	0.47	48.00	5.60	0.35	n/a	38.98	17.90	6.60	n/a
	Char	27.84	68.63	0.33	0.83	n/a	2.37	23.04	n/a	352
B	Biomass	0.85	46.97	5.82	0.06	0.31	39.52	17.08	6.32	n/a
	Char	16.08	80.23	0.49	0.23	0.28	2.69	26.64	1.04	128
C	Biomass	0.39	49.76	5.78	0.10	n/a	41.07	18.10	2.90	n/a
	Char	49.52	48.03	0.89	0.25	n/a	1.31	14.33	n/a	78
D	Biomass	0.06	49.99	5.24	0.17	0.67	41.82	17.10	3.39	n/a
	Char	31.50	66.96	0.18	0.16	0.63	0.57	19.65	81.73	281
E	Biomass	0.89	48.51	5.51	0.10	0.43	36.86	15.90	10.30	n/a
	Char	13.34	78.97	0.68	0.20	0.31	6.50	25.38	2.58	587
F	Biomass	0.41	46.83	5.92	0.06	0.33	39.84	16.55	7.65	n/a
	Char	6.49	91.59	0.52	0.25	0.56	0.60	30.81	1.59	272
G	Biomass	0.07	47.21	4.66	0.05	0.28	38.22	16.83	11.69	n/a
	Char	29.17	69.46	0.11	0.12	0.27	0.87	22.84	0.23	320
H	Biomass	0.05	48.77	6.02	0.09	0.19	37.64	16.70	8.24	n/a
	Char	25.64	69.49	0.20	0.46	0.33	3.88	24.12	2.02	306

[a] By difference; dry: dry basis; ar: as received.

the technological solution implemented on the gasifier, strongly influences the physical and chemical characteristics of chars. A similar (lack of) tendency is observed for the case of surface areas as well. In general, most of the chars have surface areas in the range 300–400 m^2/g, but some outliers can be identified. Technology E is a very interesting case, since the char has a surface area around 600 m^2/g, suggesting that an accurate reactor design could particularly influence the characteristics of chars and make it exploitable for nobler applications as activated carbon [19]. A possible explanation for this is that a preliminary feedstock carbonization step, as it occurs typically in dual-stage gasifiers, creates some intermediate aliphatic hydrocarbons. The transformation of these aliphatic C compounds into aromatic C hydrocarbons with stable rings has been proven to increase the porosity of char [53]. Recent studies, e.g. Benedetti et al. [19], showed that increased gasification temperatures result to higher char porosities and that the specific surface areas associated to char from dual-stage gasifiers are among the largest.

The management of char currently represents a significant problem for the operator of a gasification plant, also because its disposal involves a cost that is not negligible in the economic balance of the investment. In fact, char is currently treated as a waste and discarded in accordance with the European Waste Catalogue (European Directive 75/442/EEC), since there is not a specific normative for handling the solid by-products of gasification processes. For this reason, in order to understand if this material could be used as soil improver, a deeper characterization of the solid residues has been performed to determine the contents of heavy metals, dioxins, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs). As regards Italy, the Italian Legislative Decree No. 75/2010, adapted from the European Regulation No. 2003/2003, sets the specifications for using char as a fertilizer in agriculture. Among the others, it is specified that the amount of PCBs and PAHs in the char should not exceed 0.5 mg/kg and 6 mg/kg, respectively, while dioxins should not exceed 9 ng/kg. The results of the chemical analyses performed on the selected chars are reported in Table 3, in which the contents of heavy metals, dioxins, PCBs, and PAHs are shown for each char.

A considerable presence of chrome and zinc can be observed in most of the chars. These metals may derive from the metal parts of the automation devices inside the gasifiers (e.g. augers), as well as from the mechanical pre-treatment and processing of biomass, such as chipping or pelletizing.

The dioxins content is very low, mostly below the detection limits (<0.1 ng/kg), for all the analyzed char samples, and the content of PCBs is as well generally limited for most of the analyzed chars. Both for dioxins and PCBs it is therefore possible to hypothesize that the type of process and the temperature profiles involved in the gasifiers, together with the type of biomass used, contribute to limit the formation of these compounds.

Conversely, it can easily be noted that the concentrations of PAHs are not negligible and are actually definitely relevant for some chars. The presence of these toxic compounds inside the chars makes them not compliant with the current Italian legislation on fertilizers, and hence not directly useable in agriculture. Therefore, technological improvements aimed at limiting the formation and accumulation of PAHs within chars are of fundamental importance in the view of using char as a soil conditioner, as well as possible post-treatment strategies.

As regards the gaseous products obtained from the different gasification technologies considered, Fig. 4 shows the molar composition of the producer gases along with the corresponding heating values. A boxplot representation is superimposed to provide an aggregate view of all the results, useful to appreciate and visualize the range of variability of such parameters in small-scale gasification systems. Considering the overall range of variability among all the technologies, it can be indeed highlighted how, despite a certain variability in the composition of the producer gas – in particular for hydrogen, that shows a larger range of variation with respect to the other gases – the lower heating value is not appreciably affected by the technology.

Overall, the LHV of the producer gas ranges between 4.23 and 5.56 MJ/kg, with a standard deviation of 0.42 MJ/kg. Lower nitrogen fractions and thus higher producer gas heating values can be observed for technologies B and E, characterized by applying reverse downdraft reactors, and typically requiring less input of oxidizing agent (i.e. air). Another peculiarity can be appreciated as regards technology H, which shows less hydrogen but higher methane concentration than other technologies. Usually this gas distribution is observed in gasifiers that operate with lower temperature profiles in the reduction zone, which favor the hydrogasification (methanation) reaction and thus the conversion of hydrogen into methane with the presence of char.

3.3. *Quantitative mass and energy analyses and overall gasification performances*

Table 4 reports the mass flows for inputs (dry biomass and air) and outputs (producer gas and char) for each technology.

The mass balance closure was met with a satisfying degree of success, with the maximum percentage error equal to −5.37% (technology B) and the minimum equal to −0.74% (technology G). These errors were mostly generated by the propagation of the operative errors during the monitoring activities. In particular, it was not always possible to directly measure all the input parameters for the mass balance evaluation, and sometimes it was only possible to record data from the controlling system of the plant itself without a precise indication of the instrument sensitivity. Fig. 5 reports the variability of the mass balance constituents for the monitored technologies, normalized per unit mass of dry feedstock input.

Although char yield is the parameter that shows the greatest variability, it is worth mentioning how the monitored technologies are optimized to maximize gas (and consequently CHP) production, confining the char yield well below the 5% and typically in the range of 1–2%. The boxplot representation of Fig. 5 appears particularly useful to provide some characteristic range of operation for small-scale gasification technologies; 1.6–1.8 kg of air are typically necessary to gasify 1 kg of dry biomass and therefore to produce 2.5–2.8 kg of producer gas.

Energy flows for the different technologies analyzed are presented as Sankey diagrams in Fig. 6, with reference to 1 h of continuous operation. The diagram for technology B shows a second input on the ICE section since this technology is based on a dual-fuel engine and a share of about 5% of the input energy to the ICE is provided through about 2 kg/h of diesel fuel.

In respect to the gasifier thermal losses, it should be pointed out that there are some technologies that operate with minimal losses, e.g. 2.5 and 3.8% for technologies E and F, respectively, while other technologies, such as technologies A and H, have significantly higher losses, accounting for 22.1 and 26.5%, respectively. On average, energy losses represent 15.6% of the energy content of the input biomass. Interestingly, the two technologies with lower thermal losses (E and F) are both dual stage gasifiers, in which the thermal energy of the producer gas is partly used during the preliminary stage of carbonization of the raw feedstock. Biomass conversion into producer gas ranges between 66.2% (technology H) and 91.3% (technology E), with an average value of 74.3%. This efficiency was calculated by dividing the energy of the producer gas by the energy of the biomass, recovering the concept of Cold Gas

Table 3
Chemical analyses on gasification chars in terms of contents of heavy metals, dioxins, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs).

			A	B	C	D	E	F	G	H
Heavy metals	Li	[mg/kg]	9.9	8.7	6.9	9.1	9.6	8.0	6.8	10.4
	Na	[mg/kg]	268.4	1724.9	235.7	495.1	341.8	238.0	450.1	576.8
	Mg	[mg/kg]	5522.6	4802.7	11467.5	4931.4	3680.8	1562.4	9330.9	4268.6
	Al	[mg/kg]	803.2	299.6	988.5	7081.8	488.4	141.9	680.3	165.9
	K	[mg/kg]	18570.4	14810.4	18974.8	14106.5	12273.9	6429.8	31825.2	15711.6
	Ca	[mg/kg]	4670.3	14528.7	3400.4	11431.8	14790.1	10792.5	4621.6	16714.4
	Ti	[mg/kg]	36.4	40.7	47.7	38.9	46.1	13.0	35.7	23.0
	V	[mg/kg]	1.0	0.6	1.3	0.9	3.2	0.3	1.0	0.5
	Cr	[mg/kg]	6.6	5.3	14.3	3.9	383.3	2.7	16.7	28.7
	Mn	[mg/kg]	3036.3	5154.0	7056.8	839.1	903.9	557.3	2905.9	3408.0
	Fe	[mg/kg]	615.9	511.9	2509.3	589.3	2162.1	138.2	759.7	351.0
	Co	[mg/kg]	0.9	3.0	3.1	0.5	4.3	1.3	8.1	1.8
	Ni	[mg/kg]	6.6	12.8	16.5	5.3	274.2	4.2	40.6	61.9
	Cu	[mg/kg]	34.4	54.9	73.3	26.5	24.8	8.0	46.9	34.6
	Zn	[mg/kg]	478.1	449.7	1316.9	182.6	263.1	84.0	397.4	346.6
	As	[mg/kg]	1.1	0.3	0.7	0.5	0.7	0.2	0.6	0.2
	Se	[mg/kg]	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.1
	Rb	[mg/kg]	41.8	71.1	43.3	35.1	21.3	15.3	73.9	43.1
	Sr	[mg/kg]	50.5	48.8	57.8	38.8	65.2	60.8	26.1	55.8
	Mo	[mg/kg]	0.9	1.5	2.1	0.7	7.3	0.4	2.6	1.5
	Cd	[mg/kg]	1.5	5.9	0.1	1.7	1.8	0.5	0.4	0.1
	Sn	[mg/kg]	1.1	1.1	0.7	0.8	1.2	0.8	0.8	0.9
	Sb	[mg/kg]	0.1	0.2	0.1	0.1	0.2	0.0	0.3	0.1
	Ba	[mg/kg]	26.4	42.4	15.5	57.2	41.1	69.8	29.4	34.5
	Tl	[mg/kg]	0.3	0.8	0.0	0.2	0.2	0.1	0.2	0.0
	Pb	[mg/kg]	0.4	1.6	0.2	0.4	0.4	0.7	0.4	0.3
Dioxins	2378 TCDD	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	12378 PCDD	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	123478 HxCDD	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	123678 HxCDD	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	123789 HxCDD	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	1,234,678 HpCDD	[ng/kg]	<0.1	<0.1	<0.1	<0.1	0.1	0.3	<0.1	<0.1
	OCDD	[ng/kg]	2.7	1.5	1.2	0.6	2.1	2.2	0.7	2.2
	2378 TCDF	[ng/kg]	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	0.1
	12378 PCDF	[ng/kg]	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	23478 PCDF	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	123478 HxCDF	[ng/kg]	0.1	<0.1	<0.1	<0.1	<0.1	0.2	<0.1	<0.1
	123678 HxCDF	[ng/kg]	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	234678 HxCDF	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	123789 HxCDF	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	1,234,678 HpCDF	[ng/kg]	0.3	0.1	<0.1	0.1	<0.1	0.2	<0.1	0.3
	1,234,789 HpCDF	[ng/kg]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	OCDF	[ng/kg]	<0.1	0.6	<0.1	0.4	2.4	0.6	<0.1	<0.1
	Total dioxins	[ng/kg]	3.2	2.2	1.3	1.1	4.7	3.5	0.7	2.6
Polychlorinated biphenyls (PCBs)	Iupac77	[ng/kg]	10	<1	4	9	7	6	5	8
	Iupac81	[ng/kg]	<1	<1	<1	<1	<1	<1	<1	<1
	Iupac123	[ng/kg]	7	<1	10	10	8	4	1	7
	Iupac118	[ng/kg]	347	391	252	410	292	282	518	248
	Iupac114	[ng/kg]	1	2	<1	4	<1	<1	<1	2
	Iupac105	[ng/kg]	59	6	39	95	45	59	53	52
	Iupac126	[ng/kg]	<1	<1	<1	<1	<1	<1	<1	<1
	Iupac167	[ng/kg]	50	54	49	59	43	49	65	49
	Iupac156	[ng/kg]	173	224	118	142	81	133	230	120
	Iupac157	[ng/kg]	15	11	12	15	10	13	17	13
	Iupac169	[ng/kg]	<1	<1	1	2	<1	<1	<1	<1
	Iupac189	[ng/kg]	19	1	13	18	14	15	11	18
	Total PCBs	[ng/kg]	681	689	498	764	500	561	900	517
Polycyclic Aromatic Hydrocarbons (PAHs)	Naphthalene	[µg/kg]	2,128,649	1,912,973	2386	200368	859491	110338	26861	563819
	Acenaphthylene	[µg/kg]	514300	171045	138	19495	62838	140	7	62703
	Acenaphthene	[µg/kg]	314055	11197	26	1565	29918	515	270	4536
	Fluorene	[µg/kg]	16341	5287	13	27	86	203	1650	367
	Phenanthrene	[µg/kg]	584386	385187	119	78749	190237	9806	1220	118217
	Anthracene	[µg/kg]	412102	40452	18	6351	13454	457	1245	25644
	Fluoranthene	[µg/kg]	477586	47703	36	4934	29200	1218	114	46343
	Pyrene	[µg/kg]	434026	51745	22	4160	38312	817	60	44436
	BaA	[µg/kg]	104671	3742	4	226	547	20	21	12673
	CHR	[µg/kg]	135638	4514	5	236	892	220	26	25125
	B(*b*)F	[µg/kg]	32126	630	3	27	119	17	5	5197
	B(*j*)F	[µg/kg]	14180	251	2	7	29	12	2	3318
	B(k)F	[µg/kg]	10309	217	6	14	38	13	1	2170
	BeP	[µg/kg]	20993	722	3	25	107	73	41	8817
	BaP	[µg/kg]	14709	458	4	15	51	5	66	4349
	Per	[µg/kg]	3273	100	3	7	24	16	38	866
	BghiP	[µg/kg]	1632	58	1	1	17	0	1	1658

Table 3 (*continued*)

		A	B	C	D	E	F	G	H
IcdP	[μg/kg]	1921	49	1	2	2	2	1	967
DBahA	[μg/kg]	1066	30	1	0	2	2	2	771
DBalP	[μg/kg]	290	21	6	3	2	11	25	393
DBaeP	[μg/kg]	492	12	8	2	2	4	28	211
DBaiP	[μg/kg]	70	11	13	2	6	6	20	20
DBahP	[μg/kg]	151	87	27	3	9	19	51	29
Total PAHs	[μg/kg]	5,222,966	2,636,491	2845	316219	1,225,383	123914	31755	932629

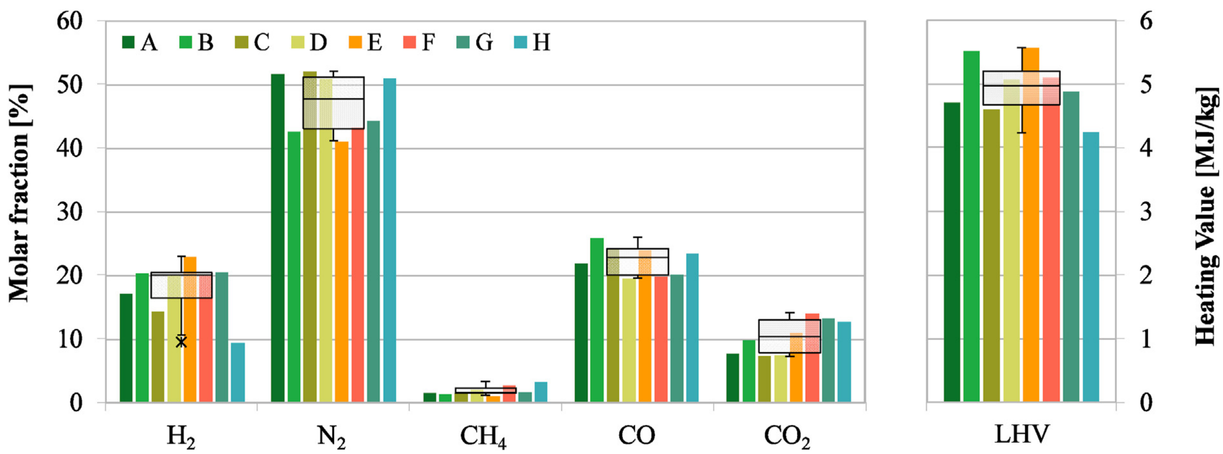

Fig. 4. Molar composition and LHV of producer gases from the eight different technologies, with superimposed boxplot representation to visualize the range of variability.

Table 4
Mass flows of the different gasification technologies.

Technology	Dry biomass	Air	Producer gas	Char
	[kg/h]	[kg/h]	[kg/h]	[kg/h]
A	39.60	68.79	107.65	0.74
B	127.34	205.75	313.92	1.29
C	106.40	180.51	285.87	1.04
D	123.75	184.97	297.57	5.06
E	42.64	78.19	121.32	0.74
F	228.99	363.29	558.75	22.83
G	338.36	663.00	990.35	3.60
H	150.82	296.89	426.46	1.06

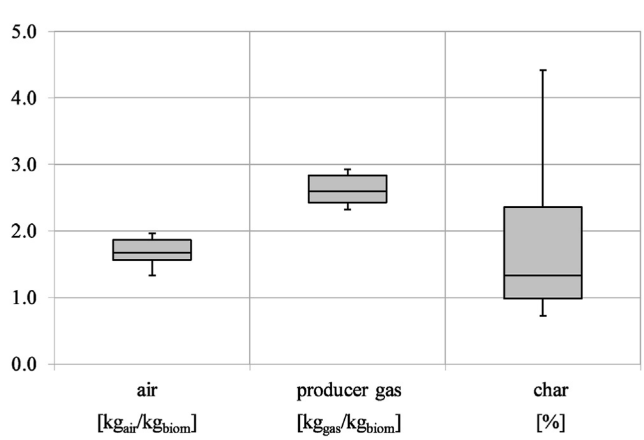

Fig. 5. Variability of mass balance constituents for the monitored technologies.

Efficiency (CGE). Furthermore, the electrical energy self-consumptions were calculated with respect to the gross electrical energy produced by each system. On average, the self-consumption accounts for 12.7%, ranging between 8.1% (technology H) and 23.8% (technology D).

The energy flows of Fig. 6 (along with the mass balances presented in Table 4) were further used to calculate the operating characteristics of the different technologies, i.e. equivalence ratio (ER), thermal, electrical and total efficiency, and the ratio between the input biomass and the output electrical power (see Table 5).

The ratio between input kg of dry biomass and electric kWh produced ranges between 0.71 and 1.05. The lowest value (i.e. 0.71 $k_{gdry\text{-}biom}/kW_{el}$) pertains to technology B, which besides exploiting a secondary fuel, uses high-quality pellets and has a high retention time. Excluding this peculiar technological solution of utilizing a dual fuel engine, a representative value for the specific electrical production of small-scale CHP systems based on biomass gasification can be therefore set at 1.10 ± 0.10 $kWh_{el}/k_{gdry\text{-}biom}$. The ER ranges between 0.25 and 0.33 (with an average of 0.28) and the CHP efficiency, indicated in Table 5 as "η_{tot}", ranges between 53.5% and 78.5%. The lowest value refers to technology H and this can be attributed to the relative conventional downdraft design that requires higher amounts of air for the autothermal process, along with the peculiar pressure drop and low temperature in the reduction zone. The highest overall efficiency value refers to technology E, which implements a dual stage gasifier. Interestingly, the high efficiency of technology E can be strictly correlated to a very high thermal efficiency, also noting that the electric one is aligned with the average (19.9%). Furthermore, the stage separation assists the optimal heat utilization for conversion and, consequently, the minimization of the energy losses. Technology B shows the highest electrical efficiency, and this can be justified by the high quality of the produced gas along with the use of a dual fuel engine, which operates with increased compression ratio than the conventional Otto engines, thus significantly increasing the thermal efficiency of the engine.

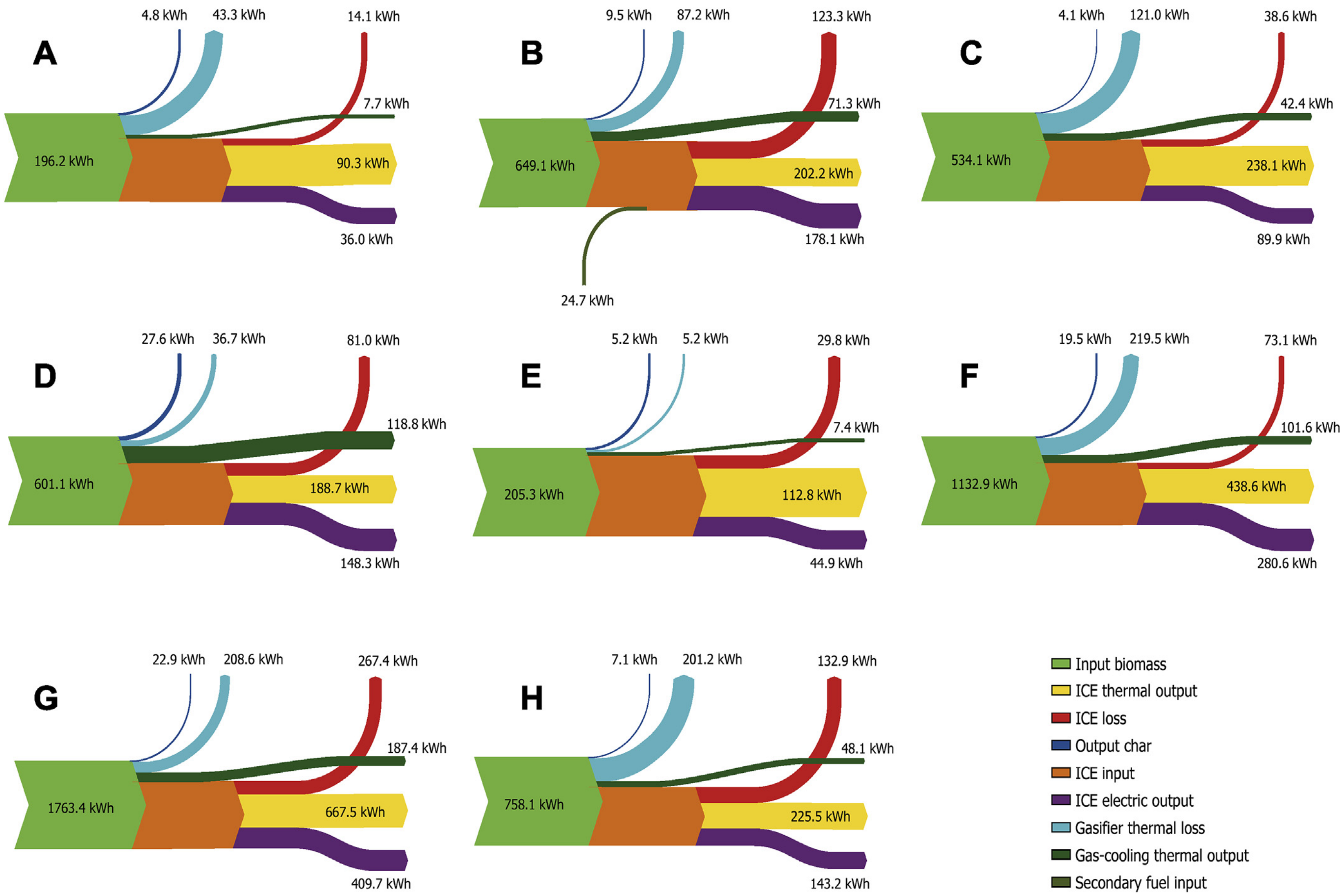

Fig. 6. Energy flow analysis of the monitored gasification technologies. The numerical values refer to 1 h of continuous operation.

Table 5
Operating characteristics of the monitored gasifiers.

Technology	ER	η_{el}	η_{th}	η_{tot}	$kg_{dry\text{-}biom}/kWh_{el}$
A	0.28	18.3	49.9	68.3	0.93
B	0.26	26.4	42.1	68.6	0.71
C	0.27	16.8	52.5	69.4	0.98
D	0.25	18.8	51.2	69.9	0.83
E	0.29	19.9	58.6	78.5	0.95
F	0.26	21.9	47.7	69.6	0.82
G	0.33	19.9	48.5	68.4	0.83
H	0.30	17.4	36.1	53.5	1.05

The effect of equivalence ratio is well documented in the literature [54] and the increased input air has been shown to have both positive and negative effects. In fact, when more input air is exploited, such as in autothermal reactors, higher temperatures profiles are reached because of a more pronounced feedstock combustion. Higher temperatures accelerate the Boudouard reaction, promoting higher carbon monoxide concentrations and lower carbon dioxide concentrations within the producer gas. In this case, typically, the quality of the producer gas is higher. However, more input air has also the effect of increasing significantly the nitrogen concentration in the producer gas and the heat losses caused by the increased temperature profiles can potentially cause further degradation of the gas quality.

Eventually, the monitoring campaign highlighted that most commercial small-scale CHPs (<200 kW_{el}) have a quite reliable operation and all manufacturers ensure 7000 h/year of operation, with 8000 h/year being the norm. Although most plants projected similar overall CHP efficiencies (approx. 70%), the distribution between electrical and thermal efficiency is strongly dependent on the intrinsic characteristics of the specific technology design. Most gasification systems have high electrical efficiency (20–30%) and as regards the by-product outputs the initial analytical results on the produced char are very promising. Nevertheless, the high-quality feedstock is a currently a fundamental prerequisite since the use of agricultural waste still presents several challenges.

4. Conclusions

Biomass exploitation is very widespread in South Tyrol (Northern Italy) especially due to its high availability. In addition, between 2010 and 2015, the Italian Government offered significant financial incentives for bioenergy production. As a result, 47 small-scale biomass gasification plants have been authorized, 42 of them are currently operating in the area and more than 10 different technologies are represented. These technologies are in principle fully automated and have interesting features that have enhanced the gasification efficiency in respect to older conventional designs. This work represents a unique overview of all the relevant gasification technologies installed in the South Tyrolean region. Complete monitoring activities have been performed on-site and both mass and energy balances have been calculated, providing an extended set of data that can be used to draw up reference values for small-scale biomass gasification systems. In particular, the analyzed technologies showed the following ranges of operation:

- Equivalence Ratio, ER: 0.28 ± 0.02;
- Cold Gas Efficiency, GCE: (74.3 ± 7.1) %;
- dry gas composition and heating value: H_2 (18.1 ± 4.1) %, N_2 (47.1 ± 4.4) %, CH_4 (1.9 ± 0.7) %, CO (22.4 ± 2.2) %, CO_2 (10.4 ± 2.6) %, LHV (4.96 ± 0.42) MJ/kg;
- specific electricity production: (1.10 ± 0.10) $kWh_{el}/kg_{dry\text{-}biom}$ – considering as outlier the higher value of 1.42 $kWh_{el}/kg_{dry\text{-}biom}$ reached by the technology implementing a dual fuel generation system;
- η_{el}: net (19.9 ± 2.9) %, gross (22.8 ± 2.4) %;
- electric self-consumptions: (12.7 ± 6.4) % of the produced electricity;
- η_{th}: (48.3 ± 6.3) %
- η_{tot}: (68.3 ± 6.4) %

Moreover, the produced chars presented some very interesting characteristics, such as a high carbon content (up to 91.6%) and a well-developed porosity, with specific surface areas up to 587 m^2/g. Char is currently disposed of and represents an economical and environmental burden. The analysis of the wood and char flows in South Tyrol, carried out through a series of questionnaires filled in by the owners of the small-scale gasification plants installed in the region, allowed to estimate that each year these systems use 49.16×10^6 kg of biomass for energy purposes, and produce 1.18×10^6 kg of char, which is disposed of with an average cost of 15 c€/kg. Despite the high metal and PAH contents that have been observed in the characterized samples do not suggest a straightforward application of gasification char as soil conditioner, its high carbon content and well-developed porosity suggest that it could be valorized and considered as a valuable commodity in industrial applications, e.g. not only for combustion, but also for gas and dye adsorption, catalyst preparation, tar cracking, or for the production of polymers. Thus, a significant milestone would be the operation of gasification plants not solely as energy production facilities but as polygenerative systems, or biorefineries. In this perspective char could be used as filtering medium, fuel and for the manufacture of other valuable products. This becomes particularly interesting in view of supporting the development of the sector, no longer sustained by the high feed-in tariffs, and offering new opportunities for ensuring the profitability of small-scale biomass gasification systems.

Credit author statement

Francesco Patuzzi: Conceptualization, Methodology, Investigation, Formal analysis, Verification, Writing – review & editing, Visualization. Daniele Basso: Investigation, Formal analysis, Writing – original draft. Stergios Vakalis: Methodology, Formal analysis, Writing – original draft. Daniele Antolini: Investigation, Methodology, Formal analysis, Verification. Stefano Piazzi: Investigation, Methodology, Writing – original draft. Vittoria Benedetti: Investigation, Writing – review & editing. Eleonora Cordioli: Investigation, Writing – review & editing. Marco Baratieri: Conceptualization, Funding acquisition, Project administration, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors want to thank the Autonomous Province of Bozen/Bolzano for the financial support to the NEXT Generation project (Novel EXtension of biomass poly-GENERATION to small-scale gasification systems in South Tyrol, Funding Agreement n. 20/34 of November 03, 2016) and the European Regional Development Fund of the European Union and the Autonomous Province of Bozen/Bolzano for the financial support to the WOOD-UP project (Optimization of WOOD gasification chain in South Tyrol to produce bioenergy and other high-value green products to enhance soil fertility and mitigate climate change, EFRE-FESR 2014–2020, project number FESR1028). Within the framework of the NEXT Generation project the following activities have been performed: monitoring activities, physical and chemical analyses on chars (a part those on heavy metals, dioxins, PCBs and PAHs), characterization of the producer gases, mass and energy balances of the monitored plants. Within the framework of the WOOD-UP project the following activities have been performed: mapping of the plants, analysis of wood and char flows in South Tyrol, chemical analyses on char to determine the contents of heavy metals, dioxins, polychlorinated biphenyls and polycyclic aromatic hydrocarbons. Moreover, the authors thank the Department of Innovation, Research and University of the Autonomous Province of Bozen/Bolzano for covering the Open Access publication costs.

The authors also want to thank Dr. Andrea Maria Rizzo and Prof. David Chiaramonti from RE-CORD – Renewable Energy Consortium for Research and Demonstration for the support in the monitoring campaign and Stefano Dal Savio, Diego Andreasi and Elisa Bonadio from NOI Techpark Südtirol/Alto Adige, Green Technologies Unit for the support in the mapping of the plants, in gathering the contacts with the plant managers and in the management of the survey through questionnaires.

References

[1] Bajwa DS, Peterson T, Sharma N, Shojaeiarani J, Bajwa SG. A review of densified solid biomass for energy production. Renew Sustain Energy Rev 2018;96:296–305. https://doi.org/10.1016/j.rser.2018.07.040.
[2] Zhang G, Chen Y, Chen Y, Guo H. Activated biomass carbon made from bamboo as electrode material for supercapacitors. Mater Res Bull 2018;102: 391–8. https://doi.org/10.1016/j.materresbull.2018.03.006.
[3] Wang J, Qian W, He Y, Xiong Y, Song P, Wang R-M. Reutilization of discarded biomass for preparing functional polymer materials. Waste Manag 2017;65: 11–21. https://doi.org/10.1016/j.wasman.2017.04.025.
[4] Spiridon I, Darie-Nita RN, Hitruc GE, Ludwiczak J, Cianga Spiridon IA, Niculaua M. New opportunities to valorize biomass wastes into green materials. J Clean Prod 2016;133:235–42. https://doi.org/10.1016/j.jclepro.2016.05.143.
[5] Faaij A, van Ree R, Waldheim L, Olsson E, Oudhuis A, van Wijk A, et al. Gasification of biomass wastes and residues for electricity production. Biomass Bioenergy 1997;12:387–407. https://doi.org/10.1016/S0961-9534(97)00010-X.
[6] Lettner F, Timmerer H, Haselbacher P. Biomass gasification – state of the art description. Intelligent Energy – Europe (IEE); 2007.
[7] Vakalis S, Sotiropoulos A, Moustakas K, Malamis D, Vekkos K, Baratieri M. Thermochemical valorization and characterization of household biowaste. J Environ Manag 2017;203:648–54. https://doi.org/10.1016/j.jenvman.2016.04.017.
[8] Rauch R, Hrbek J, Hofbauer H. Biomass gasification for synthesis gas production and applications of the syngas. Wiley Interdiscipl Rev: Energy Environ 2014;3:343–62. https://doi.org/10.1002/wene.97.
[9] Baratieri M, Prando D. Biomass for polygeneration and district heating. Handbook of clean energy systems. Chichester, UK: John Wiley & Sons, Ltd; 2015. p. 1–23. https://doi.org/10.1002/9781118991978.hces185.
[10] Salman CA, Naqvi M, Thorin E, Yan J. Gasification process integration with existing combined heat and power plants for polygeneration of dimethyl ether or methanol: a detailed profitability analysis. Appl Energy 2018;226: 116–28. https://doi.org/10.1016/j.apenergy.2018.05.069.
[11] Parraga J, Khalilpour KR, Vassallo A. Polygeneration with biomass-integrated gasification combined cycle process: review and prospective. Renew Sustain Energy Rev 2018;92:219–34. https://doi.org/10.1016/j.rser.2018.04.055.
[12] Kraussler M, Binder M, Schindler P, Hofbauer H. Hydrogen production within a polygeneration concept based on dual fluidized bed biomass steam gasification. Biomass Bioenergy 2018;111:320–9. https://doi.org/10.1016/j.biombioe.2016.12.008.
[13] Bräkow D. Biomass gasification 2007-2017 - technology development and protagonists. International conference on application of biomass gasification.

2017. Innsbruck.
[14] Provincia Autonoma di Bolzano – Alto Adige. Relazione agraria & forestale 2018. Italy: Bolzano; 2019.
[15] Vakalis S, Baratieri M. State-of-the-Art of small scale biomass gasifiers in the region of South Tyrol. Waste and Biomass Valor 2015;6:817–29. https://doi.org/10.1007/s12649-015-9398-8.
[16] Ahmad J, Patuzzi F, Prando D, Castaldi MJ, Baratieri M. Possible utilization pathways of char from real scale biomass gasifiers. In: Nzihou A, editor. 6th international conference on engineering for waste and biomass valorisation (WasteEng 2016). Albi, France: Mines Albi; 2016. p. 881–9.
[17] Vakalis S, Patuzzi F, Baratieri M. Introduction of an energy efficiency tool for small scale biomass gasifiers – a thermodynamic approach. Energy Convers Manag 2017;131:1–9. https://doi.org/10.1016/j.enconman.2016.11.022.
[18] Baratieri M. A case study of gasification CHP in northern Italy in the European context and comparison to traditional combustion systems. In: Castaldi MJ, Patuzzi F, Ciuta S, Tupsakhare S, Tsiamis D, editors. Proceedings of 2018 EEC/WTERT conference. New York: ASME Press; 2019. p. 19–22. https://doi.org/10.1115/1.861950.
[19] Benedetti V, Patuzzi F, Baratieri M. Characterization of char from biomass gasification and its similarities with activated carbon in adsorption applications. Appl Energy 2018;227:92–9. https://doi.org/10.1016/j.apenergy.2017.08.076.
[20] Galhetas M, Lopes H, Freire M, Abelha P, Pinto F, Gulyurtlu I. Characterization, leachability and valorization through combustion of residual chars from gasification of coals with pine. Waste Manag 2012;32:769–79. https://doi.org/10.1016/j.wasman.2011.08.021.
[21] Piazzi S, Zhang X, Patuzzi F, Baratieri M. Techno-economic assessment of turning gasification-based waste char into energy: a case study in South-Tyrol. Waste Manag 2020;105:550–9. https://doi.org/10.1016/j.wasman.2020.02.038.
[22] Runtti H, Tuomikoski S, Kangas T, Lassi U, Kuokkanen T, Rämö J. Chemically activated carbon residue from biomass gasification as a sorbent for iron(II), copper(II) and nickel(II) ions. J Water Process Eng 2014;4:12–24. https://doi.org/10.1016/j.jwpe.2014.08.009.
[23] Marchelli F, Cordioli E, Patuzzi F, Sisani E, Barelli L, Baratieri M, et al. Experimental study on H_2S adsorption on gasification char under different operative conditions. Biomass Bioenergy 2019;126:106–16. https://doi.org/10.1016/j.biombioe.2019.05.003.
[24] Benedetti V, Cordioli E, Patuzzi F, Baratieri M. CO_2 Adsorption study on pure and chemically activated chars derived from commercial biomass gasifiers. J CO2 Util 2019;33:46–54. https://doi.org/10.1016/j.jcou.2019.05.008.
[25] Benedetti V, Ail SS, Patuzzi F, Baratieri M. Valorization of char from biomass gasification as catalyst support in dry reforming of methane. Front Chem 2019;7:1–12. https://doi.org/10.3389/fchem.2019.00119.
[26] Benedetti V, Ail SS, Patuzzi F, Cristofori D, Rauch R, Baratieri M. Investigating the feasibility of valorizing residual char from biomass gasification as catalyst support in Fischer-Tropsch synthesis. Renew Energy 2020;147:884–94. https://doi.org/10.1016/j.renene.2019.09.050.
[27] Klinghoffer NB, Castaldi MJ, Nzihou A. Catalyst properties and catalytic performance of char from biomass gasification. Ind Eng Chem Res 2012;51: 13113–22. https://doi.org/10.1021/ie3014082.
[28] Cordioli Patuzzi, Baratieri. Thermal and catalytic cracking of toluene using char from commercial gasification systems. Energies 2019;12:3764. https://doi.org/10.3390/en12193764.
[29] Hansen V, Müller-Stöver D, Ahrenfeldt J, Holm JK, Henriksen UB, Hauggaard-Nielsen H. Gasification biochar as a valuable by-product for carbon sequestration and soil amendment. Biomass Bioenergy 2015;72:300–8. https://doi.org/10.1016/j.biombioe.2014.10.013.
[30] GSE. Atlaimpianti - L'atlante geografico delle rinnovabili [Online], www.gse.it/dati-e-scenari/atlaimpianti. [Accessed 20 August 2020].
[31] Provincia Autonoma di Bolzano – Alto Adige. Agenzia provinciale per l'ambiente e la tutela del clima [Online], https://ambiente.provincia.bz.it/. [Accessed 20 August 2020].
[32] Weichselbaum K. Method and device for thermochemically gasifying solid fuels. Patent number: WO2010046222; 2010.
[33] Burkhardt GmbH. Wood gasification with wood pellets: our technology [Online] n.d. https://burkhardt-gruppe.de/en/power-engineering/heat-and-power-from-wood/wood-gas-generator/. [Accessed 21 August 2020].
[34] Senger M, Hofmeister M, Dressler H, Uhlig J. Downdraft fixed-bed gasifier for producing a product gas from pourable biomass particles. 2017. Patent number: US20170275543.
[35] Dany C. Minikraftwerk ersetzt dieselmotor [Online], https://www.vdi-nachrichten.com/technik/minikraftwerk-ersetzt-dieselmotor/. [Accessed 21 August 2020].
[36] Wegscheid Holzenergie. Saubere Energie herstellen und dabei Geld verdienen? Wir haben die Lösung! [Online], http://www.holzenergie-wegscheid.de/. [Accessed 28 August 2020].
[37] Kuntschar W. Cocurrent gasifier. 2005. Patent number: EP1616932.
[38] Joos B. Device for creating a flammable gas mixture. 2012. Patent number: EP2522707.
[39] Seidel S. Biomass power plant from Spanner Re^2 [Online] 2020, https://www.holz-kraft.com/en/. [Accessed 28 August 2020].
[40] Egeler R, Sewald W, Waller R, Artmann K. Method and device for gasifying biomass. Patent number: WO2011134961. 2011.
[41] Huber MB. Gasification process with a reduction process in a stable floating bed. Patent number: ep2129749. 2008.
[42] Engineering GmbH SynCraft. SYNCRAFT® - das holzkraftwerk [Online], https://en.syncraft.at/. [Accessed 20 August 2020].
[43] Urbas P, Ebenberger P, Felsberger W. Wood gasification system. Patent number: WO2008089503; 2008.
[44] Maschinenfabrik GmbH Urbas. Energietechnik - URBAS Energietechnik und Stahlbau [Online], https://www.urbas.at/en/energietechnik/. [Accessed 20 August 2020].
[45] Patuzzi F, Prando D, Vakalis S, Rizzo AM, Chiaramonti D, Tirler W, et al. Small-scale biomass gasification CHP systems: comparative performance assessment and monitoring experiences in South Tyrol (Italy). Energy 2016;112:285–93. https://doi.org/10.1016/j.energy.2016.06.077.
[46] Vakalis S, Prando D, Patuzzi F, Mimmo T, Gasparella A, Tirler W, et al. Experiences in biomass gasification in South-Tyrol: the "GAST" project. In: ETA florence. Copenhagen, Denmark: 21st European Biomass Conference & Exhibition; 2013. p. 891–901. https://doi.org/10.5071/21stEUBCE2013-2CV.3.61.
[47] Bates R, Dölle K. Syngas use in internal combustion engines - a review. Adv Res 2017;10:1–8. https://doi.org/10.9734/air/2017/32896.
[48] Hagos FY, Aziz ARA, Sulaiman SA. Trends of syngas as a fuel in internal combustion engines. Adv Mech Eng 2014. https://doi.org/10.1155/2014/401587. 2014.
[49] Caligiuri C, Antolini D, Patuzzi F, Renzi M, Baratieri M. Modelling of a small scale energy conversion system based on an open top gasifier coupled with a dual fuel diesel engine. In: ETA florence. Stockholm, Sweden: 25th European Biomass Conference and Exhibition; 2017. p. 788–93. https://doi.org/10.5071/25thEUBCE2017-2CV.3.22.
[50] Boloy RAM, Silveira JL, Tuna CE, Coronado CR, Antunes JS. Ecological impacts from syngas burning in internal combustion engine: technical and economic aspects. Renew Sustain Energy Rev 2011;15:5194–201. https://doi.org/10.1016/j.rser.2011.04.009.
[51] Pedrazzi S, Allesina G, Morselli N, Puglia M, Rinaldini CA, Savioli T, et al. Modified diesel engine fueled by syngas: modeling and experimental validation. European Biomass Conference and Exhibition Proceedings; 2016. 2016.
[52] Benson SA, Sondreal EA. Ash-related issues during combustion and gasification. Imp Miner Impur Solid Fuel Combust 2005;1–21. https://doi.org/10.1007/0-306-46920-0_1.
[53] Komnitsas K, Zaharaki D, Pyliotis I, Vamvuka D, Bartzas G. Assessment of pistachio shell biochar quality and its potential for adsorption of heavy metals. Waste and Biomass Valor 2015;6:805–16. https://doi.org/10.1007/s12649-015-9364-5.
[54] Upadhyay DS, Sakhiya AK, Panchal K, Patel AH, Patel RN. Effect of equivalence ratio on the performance of the downdraft gasifier – an experimental and modelling approach. Energy 2019;168:833–46. https://doi.org/10.1016/j.energy.2018.11.133.