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Title

Techno-economic assessment of turning gasification-based waste char into energy: a case study in South-Tyrol

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Abstract

In the South-Tyrol region (Italy), 46 gasifiers are currently operating and €200,000 are annually paid to dispose of as a waste 1300 tons of char. Therefore, there is a considerable interest in finding alternatives for the valorization of this solid by-product. The aim of this work is to assess the potential of char as energy source and to compare two scenarios. The first scenario considers the possibility of exploiting char in a dedicated burner integrated in the gasification plant. The second scenario assumes that all the char is collected from South-Tyrol and co-fired with biomass in an existing combustion-ORC plant. An economic analysis was performed evaluating the discounted payback time and both scenarios were modeled using Aspen Plus®. The results reveal that substantial savings in the operating costs of the plants can be achieved. In the first scenario the owners of the gasification plants could save from 50% to 94% of the char disposal costs with a payback time ranging between 3 and 7 years. In the second scenario, the owner of the plant could save approximately €235k per year with a payback time of approximately 7 years. The present study provides a basis for further techno-economic studies on char combustion. The results can be helpful for the owners of the gasification plants in determining the most cost-effective way to dispose char and to avoid disposing it of as a waste. Furthermore, it is demonstrated how char could be used as a renewable fuel, with better performance than raw biomass.

Keywords

char; waste; gasification; combustion; economic analysis; system model.

Abbreviations		**Symbols**		**Subscripts**	
CHP	Combined Heat and Power	E	Power	bio	Biomass
DH	District Heating	FC	Fixed Carbon	cond	Condensation
ER	Equivalence Ratio	LHV	Lower Heating Value	d	Design
GHG	Greenhouse gases	$\dot{m}$	Mass flow rate	el	Electric
GS	Gasification savings	P	Pressure	evap	Evaporation
HE	Heat Exchanger	T	Temperature	g	generator/motor
HRVG	Heat Recovery Vapor Generator	V	Volume	gas	Gasification
ICE	Internal Combustion Engine	VM	Volatile matter	H2O-IN	Return water temp.

IR	Interest rate	X	Vapor title	iso	Isentropic
MDM	Octamethyltrisiloxane	η	Efficiency	m	Mechanical
ORC	Organic Rankine cycle	ρ	Density	off	Off design
TG	Thermogravimetric	ε	Effectiveness	oil	Thermal oil
				rec	Recirculated
				SH	Super heating
				syn	Producer gas
				th	Thermal

1 Introduction

World energy consumption has increased significantly during the past decades and it is projected to continuously grow by 28% between 2015 and 2040 (EIA, 2017). This will lead to an increase in emissions of greenhouse gases (GHG) (British Petroleum, 2016). The European Council in 2007 adopted ambitious energy and climate change objectives for 2020 (Directorate-General for Energy, 2011) and the same has been done in 2016 by the UNFCCC (United Nations Framework Convention on Climate Change) (United Nations Framework Convention on Climate Change, 2016) at the twenty-first session of the Conference of the Parties (COP 21). One of the available options to accomplish these goals and to move towards a sustainable energy future is to maximize the use of biomass. It has the potential to partially or completely substitute fossil fuels, such as coal, and simultaneously decrease GHG emission because of its carbon neutrality. Among the available technologies to utilize biomass, one of the most interesting is gasification, which transforms the input solid fuel into a gaseous fuel, mainly composed of hydrogen, carbon monoxide, carbon dioxide and nitrogen. One of the problems related to this technology is the management of the byproducts (i.e. char), which represent both economic and energy loss (Marchelli et al., 2019). Char is a carbon-based material and its production usually ranges between 2% and 5% of the input feedstock (Vakalis et al., 2016). In the alpine region of South Tyrol, 46 gasification plants are currently operating, producing approximately 1300 tons of char every year (Basso et al., 2017), with an associated cost for the disposal of about 150 €/ton (Patuzzi et al., 2016). Nowadays char is not used in any applications and it is disposed of as a waste. However, in literature there are several studies which investigate its possible uses. The methods of valorizing this solid carbon residue are: fuel in gasifiers or combustors (Vakalis et al., 2016), domestic charcoal, activated carbon (Benedetti et al., 2018, 2016), fertilizer or soil conditioner, manure treatment, feed-additives (Alburquerque et al., 2016), tar reforming catalyst (Abu El-Rub et al., 2008; Cordioli et al., 2018) or adsorbent for hydrogen sulphide (H_2S) (Marchelli et al., 2019). Char applicability in these possible uses is dependent on its characteristics and composition (Hernandez et al., 2016); nevertheless, a common factor among different chars is the high carbon content and heating value, which makes char a suitable fuel in combustion or co-combustion scenarios (Barbanera et al., 2018; Khiari et al., 2019).

Galhetas *et al.* (Galhetas et al., 2012) investigated gasification char residues for their potential use for energy production and the studies revealed a good thermochemical behavior, without presenting any major operational risks.

Combustion of gasification char has similar advantages to biomass combustion, because of the low costs, negligible nitrogen and sulfur content and renewable nature. Besides, it has the potentialities of contributing to the solution of solid waste elimination problems, as well as reducing greenhouse gas components (Yilgin and Pehlivan, 2009).

Very few studies on char combustion are reported in literature, and most of them include investigations using thermogravimetric analyzer (TGA). These works highlight the high combustion reactivity of gasification char, compared to coal (Wornat et al., 1995) or char obtained from torrefied biomass (Fisher et al., 2012; McNamee et al., 2015). Instead, the majority of the studies focus on the evaluation of kinetic parameters, i.e. char reactivity and diffusion rate, by varying the combustion conditions, such as temperature (Pereira and Pinho, 2013), oxidizing agents (Molintas and Gupta, 2016; Ramos et al., 2012) or both of them but using temperature pertinent to commercial scale plants (Wornat et al., 1996).

While a number of studies concerning co-firing of biomass with coal are available in literature, very few studies on biomass (or coal) and char blends are reported. In regards with coal and biomass co-combustion, Spliethoff (Spliethoff, 2010) highlighted that this approach has a number of advantages even if compared with small plants fired with biomass only. Some of these advantages can also apply to char and biomass co-combustion. Firstly, the co-combustion (for low co-firing level) could be implemented in the existing plants; this means that no capital costs are needed. Secondly, the efficiency of a large co-combustion plant is always higher than a small dedicated plant. Lastly, in case of low availability of secondary fuel, there would not be any energy production problem because the plant can run with the primary fuel only. Besides, the few studies on biomass and char blends that can be found in literature, unearth interesting conclusions. Co-firing raw biomass with an addition of char can increase the heating value of the mixture; this is a straightforward consequence of the lower moisture content, higher fixed carbon and higher LHV of char than that of raw biomass. These factors also show how char is a more suitable fuel for combustion than raw biomass (Yi et al., 2013). Compared to raw or torrefied biomass, char is the preferred option when co-fired with pulverized coal (Kastanaki and Vamvuka, 2006). This is due to the fact that char is one of the most reactive carbon materials (Backreedy et al., 2003), due to its porous and highly disordered carbon structure, it gives lower operational problems while increasing the mass percentage of char (Eddings et al., 2015), it gives more heat input (heat energy per unit mass) and exhibits more synergistic features (Sarkar et al., 2014). Yi *et al.* (Yi et al., 2013), which compared the combustion characteristics of char with respect to biomass and char blends by TG analysis, discovered that blends with 10–30% by mass of char behave better than those with higher char ratio. Instead when co-firing it with coal, char-proportion in the blends may be safely raised to 50% in mass (Sahu et al., 2010; Sarkar et al., 2014). These studies indicate that there is not a linear correlation between the combustion performances and the char mass percentage increase. The thermal behavior of the blends shows some deviations from the expected weighted average of the properties of the constituent fuels. Thus, to meet the desired combustion performance and to promote the use of char as a co-fuel for power generation, a judicious selection of effective blend combination and blend proportion should be made.

Nowadays, it is a consolidated practice to combine experimental activities with process modeling. There are two main approaches for modeling gasification, based on thermodynamic (equilibrium) and kinetic (rate) models. According to Safarian *et al.* (Safarian et al., 2019) more than 60% of the gasification models available in literature adopts a thermodynamic equilibrium approach. Equilibrium modeling is indeed a convenient method to study the behavior of a fuel given some process parameters. However, some main simplifications are introduced, i.e. the method is independent of the gasifier design and it assumes that the process is carried out in fully mixed condition for an infinite period of time (Tiwary et al., 2018). Among the available options to develop this type of model, Aspen Plus® (“Aspen Plus - Webpage,” n.d.) is one of the most widely used software for simulating many thermochemical and thermodynamics processes (Cruz et al., 2017; Fan et al., 2017; Zang et al., 2019).

A similar approach has been used in this work, which explores the potential of char as an energy source in the South Tyrol region in Italy and suggests propitious solutions for char valorization. Two thermodynamic models have been developed using the software Aspen Plus® and validated with experimental data. In particular, the developed models have been used to conduct techno-economic studies to determine an economic way of disposing char. An economic analysis was performed for two scenarios, to determine the savings in the operating costs and the discounted payback time.

The basis of this work has been laid out in our earlier works (Basso et al., 2017; Patuzzi et al., 2016) related to the comprehensive analysis of the gasification technologies operational in South Tyrol region of Italy. The analysis here presented provides the basis for developing a possible mechanism for char valorization, useful for enhancing the profitability of the biomass gasification sector in South Tyrol and, more generally, for the decentralized CHP production from small-scale biomass gasification systems.

2 Model development and assessment methodology

2.1 Implemented scenarios

Two scenarios have been implemented and analyzed. The first scenario, dedicated char burner, considers the design of a dedicated on-site combustor, directly connected with the cyclone of an existing gasification plant. The second scenario, centralized char combustion, considers a centralized collection of char from all the gasification plants in the South Tyrol region, where a production of about 1300 ton/year has been estimated (Basso et al., 2017), and its co-firing with biomass in a combustion plant connected to an Organic Rankine Cycle (ORC).

The input data and the data used to validate the model are taken from our earlier works (Basso et al., 2017; Patuzzi et al., 2016), which provide in-depth analysis of eight gasification technologies operational in the region and are listed in Table 1.

Table 1 Main characteristics of the gasification technologies (Basso et al., 2017)

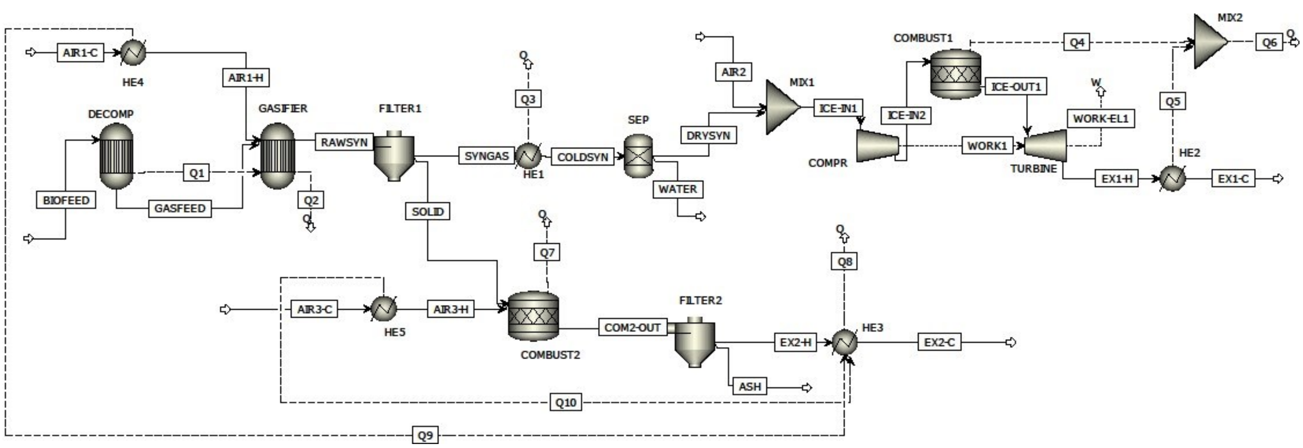
Technology	Feedstock	Reactor	Agent	kW_{el}	kW_{th}	Biomass [ton/y]	Char [ton/y]
A	Wood chips	Downdraft	Air	35-45	79-105	10,036	158
B	Pellets	Rising co-current	Air	180	270	9,778	277
C	Wood chips	Downdraft	Air	150	280	2,094	44
D	Wood chips	Downdraft	Air	199-296	320-550	10,306	445
E	Wood chips	BFB, Multistage	Air	50	110	222	8
F	Wood chips	BFB, Multistage	Air	250	990	1,721	137
G	Wood chips	Downdraft	Air	440	880	3,300	70
H	Wood chips	Downdraft	Air	140	270	1,165	2

For the Aspen Plus® model developed in this work the MIXCINC stream class was chosen, to include conventional and non-conventional elements. The Peng-Robinson equation of state with Boston-Mathias modifications (PR-BM) was selected as the property method ("Aspen Plus User Guide 10.2," 2000).

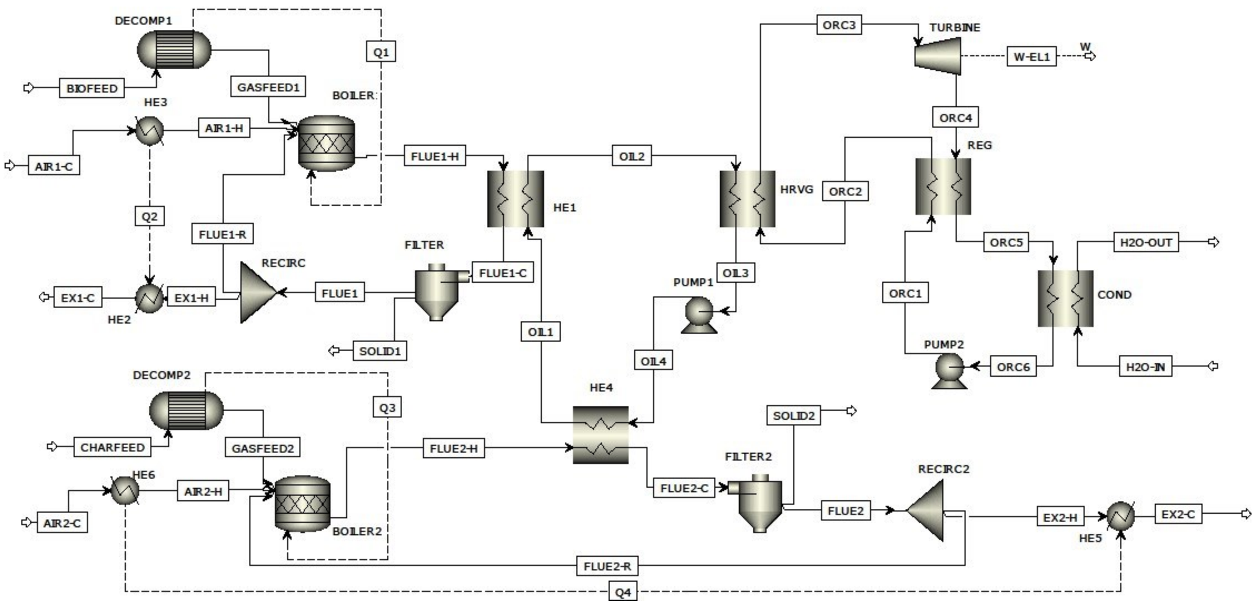
The property methods HCOALGEN and DCOALIGT were respectively chosen to calculate the enthalpy and density of non-conventional components. In this work, the heat of combustion was calculated based on the LHV of the biomass. The Aspen flowsheets of the two investigated scenarios are shown in Fig. 1 and further discussed in the related sections in the following.

2.2 Model for Scenario 1

Figure 1a describes the scheme used for analyzing Scenario 1. Biomass is fed into the gasifier, which converts it into producer gas and char. The input streams to the gasifier are the inlet biomass and the gasification agent, i.e. air. Both are characterized by their thermodynamic conditions and their composition (ref. to Table 2 for biomass). The producer gas is then cleaned and cooled before being fed in an internal combustion engine (ICE). The model considers also the utilization of the char, which is not currently implemented in the real plants. It is possible to identify three thermal energy outputs (producer gas cooling, heat recovery from the engine and char combustion) and one electrical energy output (from ICE).



(a)



(b)

Fig. 1 Aspen Plus® flowsheet a) Scenario 1, b) Scenario 2

The model is based on some main assumptions. The process is assumed to be isothermal, steady state and isobaric (atmospheric), assuming the ideal gas behavior for both reactants and products. The reactor is considered as zero-dimensional and perfectly mixed with no consideration of spatial parameters or time. Char is considered to be composed of ashes and carbon (as graphite), instead tar formation is neglected.

The gasification reaction mechanism involves several complex reactions and it generally depends on the fuel type, the gasification agent and the reactor design. Thus, in the proposed simplified model, the reaction products are evaluated considering chemical and thermodynamic equilibrium conditions. The composition of a mixture in these conditions represents the most stable composition for a reacting system. This operation can be achieved minimizing the Gibbs free energy of the products using the *RGibbs* reactor (labeled GASIFIER) and by setting the gasification temperature, pressure and the possible array of products, i.e. H_2, O_2, N_2, H_2O, C, CO, CO_2, CH_4 and ash (Formica et al., 2016). This kind of reactor does not accept non-conventional components, thus the *RYield* reactor (labeled DECOMP) has to be used to convert biomass into its elemental components. Table 2 reports the elemental composition and the heating value of the feedstock considered in the simulations.

Table 2 Elemental analysis and heating value of the initial biomass (Basso et al., 2017), the biomass used in the ORC and the South-Tyrolean char mix

Technology		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**ORC**	**Char Mix**
Moisture	$\%wt_{ar}$	6.60	6.32	2.90	3.39	10.30	7.65	11.69	8.24	8.80	-
Ash	$\%wt_{dry}$	0.50	0.92	0.40	0.06	0.97	0.44	0.08	0.05	1.10	24.66
C	$\%wt_{dry}$	51.17	50.01	51.20	51.02	52.24	49.92	51.70	52.30	50.54	72.88
H	$\%wt_{dry}$	5.97	6.20	5.95	5.35	5.94	6.31	5.10	6.46	5.97	0.34
N	$\%wt_{dry}$	0.37	0.06	0.10	0.17	0.11	0.06	0.05	0.10	0.12	0.28
S	$\%wt_{dry}$	0.00	0.33	0.00	0.68	0.47	0.36	0.31	0.20	0.00	0.40
O	$\%wt_{dry}$	41.99	42.49	42.35	42.72	40.28	42.91	42.76	40.89	42.26	1.43
LHV	MJ/kg_{dry}	19.26	18.35	18.68	17.49	17.33	17.81	18.76	18.09	19.66	23.20

A cyclone (*SSplit,* labeled FILTER1) is used to remove char particles. The output gas is then cooled to 110°C using a *Heater* block (labeled HE1). The cold producer gas is finally fed into a separator to remove the water and thus increase the heating value of the gas.

The gas produced in the gasification plant is combusted in an internal combustion engine. The operating data have been selected in order to represent the values of a real engine and to obtain a similar energy (electrical and thermal) output as the one measured by Patuzzi *et al.* (Patuzzi et al., 2016) . The Otto cycle is modeled in Aspen Plus® as a gas turbine with the main difference that fuel and combustion air are mixed before the compression stage and not in the combustion chamber (Megwai and Richards, 2016).

As shown in Figure 1a, the internal combustion engine is subdivided in three blocks: 1. Compression block (labeled COMPR), where the working fluid (producer gas and air) is compressed. The final pressure is set at 20 bar, the isentropic efficiency is set at 0.8 and the mechanical efficiency is set at 0.98 (Monteiro et al., 2012). The compressor works with the work supplied by the turbine; 2. Combustion block (labeled COMBUST1), where the compressed fluid is burnt at constant volume. Within this block, the combustion temperature and pressure are set at 1600°C and 70 bar respectively (Gamiño and Aguillón, 2010; Monteiro et al., 2012). The oil and the water of the engine are cooled, and the heat is channeled into a heat stream; 3. Expansion block (labeled TURBINE), where the exhaust gases are expanded to obtain work. The final pressure is set at 2 bar, the isentropic efficiency at 0.8 and the mechanical efficiency at 0.98 (as the compressor) (Monteiro et al., 2012).

The integrated char burner is fed by the stream of char that discharges from the cyclone of the gasification plant. The mass fractions of hydrogen, nitrogen and oxygen in the char are negligible (<3%). Thus, char has been considered as a mix of just ash and carbon. The combustion occurs in a *RStoic* reactor (labeled COMBUST2) at 1100°C and 1 bar. The exhaust gas, which is mainly composed of permanent gases, i.e. CO_2, N_2 and H_2O, is cleaned in a filter that removes the ashes.

The flue gas is finally cooled in a heat exchanger, decreasing its temperature to 150°C. The heat extracted from the flue gas has been partially used to pre-heat air streams from 25°C to 250°C.

This is done both for gasification air and for the char combustion air.

2.3 Model for Scenario 2

The implementation of the second scenario foresees the modeling of an Organic Rankine Cycle, i.e. ORC generator coupled with a biomass boiler. The model is validated by means of data set measured at a real scale plant located in the district of Renon in South-Tyrol (Italy) (Prando et al., 2015). This scenario considers the collection of the char from the entire region and its combustion in the ORC plant. The original plant scheme is modified including a char burner. Figure 1b shows the flowsheet of the model developed in Aspen Plus®, which simulates a parallel co-combustion. This solution is more expensive than direct co-combustion, requiring a separate burner; however it is more efficient (the combustion conditions can be set according to the characteristics of biomass and char separately) and it allows to use as much char as desired, without being constrained by the co-firing ratio (Agbor et al., 2014). Furthermore, the heat generated by the combustion of the two fuels is kept separated, allowing understanding and quantifying, through the model, the benefits derived from the co-combustion of char (Agbor et al., 2014).

The properties and the way to import the biomass in Aspen Plus® are the same as for the previous model (section 2.3). Two more substances were considered for this model: 1) OctaMethylTriSiloxane: also known as MDM, with chemical formula $C_8H_{24}Si_3O_2$ which has been considered as working fluid of the ORC cycle; 2) Dowtherm-RP: this component, available in the Aspen Plus® database, has been used to simulate the thermal oil used in the boiler, i.e. Diphyl THT, given its similar thermophysical properties (molecular weight 236.4 g/mol, boiling temperature 352°C, range of application 0-350°C).

Pre-heated air and biomass (Table 2) are fed together to a combustion *RStoic* reactor (labeled BOILER1). The hot flue gases first pass through a heat exchanger where heat is transferred to the thermal oil and then a cyclone removes the solid particles (ash). Subsequently, a three-way valve, represented with a *FSplit* block (labeled RECIRC), recirculates part of the flue gases to decrease the production of nitrogen oxides.

The hot thermal oil is used to heat at constant pressure the working fluid (MDM) of the ORC. In the HRVG the MDM vapor title passes from 0 to 1, becoming a dry saturated vapor; a super-heating of 3°C is adopted in the boiler to ensure the complete evaporation of the working fluid (Prando et al., 2015). The working fluid is then expanded in the turbine where the output pressure and the efficiencies (mechanical and isentropic) are given as input; this block generates the electrical work output by running a generator. Next, in the regenerator the vapor exchanges some of its enthalpy with the liquid working fluid, in order to increase the efficiency of the overall cycle. Finally, the vapor enters the condenser in which the thermal energy is released to the water flow of the district heating network; here the vapor is transformed into a saturated liquid through a constant pressure process. On the other side of the condenser a water stream is used as cooling fluid. The input conditions of the water depend on the user and in partial load conditions this is the input that regulates the entire plant.

A weighted average char composition has been evaluated, according to the actual number of modules installed in South-Tyrol for each considered technology and the corresponding char production (Table 1). The obtained "Char Mix" characteristics are reported in Table 2 and are used in a *RYield* reactor (labeled DECOMP2) to convert the element char rom a non-conventional element to conventional elements. Char is burnt in a *RStoic* reactor (labeled BOILER2) and the flue gases are used to heat the thermal oil exiting the HRVG using a heat exchanger (*MHeatX*). The flue gases are then released in the atmosphere after a few cleaning stages.

Nominal operating conditions (see Table S1) are characterized by an electrical output of 1.1 MW_{el} and a return water temperature of the district heating (DH) network of 58°C; instead, partial load operations correspond to a higher temperature of the return water of the DH and consequently a lower electrical output.

In partial load operation, the mass flow of MDM has to be modified in order to keep the district heating supply temperature at 90°C (nominal condition). To achieve this, a "design specs block", with a FORTRAN routine, was used.

The other input parameters that are affected by off-design conditions are the turbine isentropic efficiency, the condensing and evaporating pressure, the outlet temperature from the regenerator and the biomass mass flow.

Regarding the isentropic efficiency, Prando *et al.* (Prando et al., 2015) report the equation proposed by Keeley (Keeley, 1988):

$$\eta_{is,off} = \eta_{is,d} \cdot \sin\left[\frac{\pi}{2}\left(\frac{\dot{m}_{v,off} \cdot \rho_d}{\dot{m}_{v,d} \cdot \rho_{off}}\right)\right] \quad (1)$$

This equation was implemented in a calculator block that re-calculates the off-design isentropic efficiency every time the mass flow of MDM changes.

To evaluate how the condensing and evaporating pressure change in off-design operation, a correlation among the measured data of the reference (Prando et al., 2015) was estimated. Known the mass flow rate ($\dot{m}$) and the corresponding pressures (P), the performance curves of the turbine and of the pump were determined in the form of Equation 2.

$$P = a + b \cdot \dot{m} + c \cdot \dot{m}^2 \quad (2)$$

Where the three coefficients a, b, and c are 12.374, 1.633, and -0.0698 for condensation pressure and -983.18, 184.51, and -4.1385 for evaporation pressure, respectively.

2.4 Assessment of the economic feasibility

A techno-economic analysis of the two proposed scenarios has been carried out.

To estimate the profitability of the integrated char burner (Scenario 1), the capital and operation and maintenance (O&M) costs should be compared with the advantages related to the direct combustion of char, e.g. fuel saved to pre-heat gasification air, money saved in the disposal of char. Once the char is fully oxidized, the only residue is represented by the ashes, leading to a reduction in weight and a subsequent decrease of disposal costs. A parameter named "gasification savings" (GS) has been defined as the relative difference between disposal costs with and without the integrated char burner. The GS are strictly correlated with the ash content; the lower the amount, the higher the GS.

The following procedure has been applied in order to analyze the variation of the cash flow due to the use of the char for the centralized char combustion plant (Scenario 2). The price of woodchip has been assumed at 120 €/t and for char and ash disposal cost of 150€/t has been considered (Patuzzi et al., 2015; Prando et al., 2015). These costs are overall costs paid by the owners of the plants - retrieved from them after a series of surveys and questionnaires - and include the cost of the raw material, the logistic fees and the taxation. The 2008 (year of authorization of the ORC plant) Italian price of electrical energy produced using biomass corresponds to 0.28 €/kWh (“Gestore Servizi Energetici,” n.d.). The capital costs of the equipment (Cost) have been determined using the Chemical Engineering Plant Cost Index (CEPCI), which takes into account the time value of money, and the exponential method, known as the six-tenths rule (Don W. Green, 2008), which considers the size of the boiler (Capacity):

$$Cost_B = Cost_A \cdot \left(\frac{Capacity_B}{Capacity_A}\right)^{0.6} \cdot \left(\frac{CEPCI_{year2}}{CEPCI_{year1}}\right) \quad (3)$$

Where *A* and *B* refers to different size plants, *year1* to the cost of plant *A* in the base year and *year2* to the cost of plant *B* in the selected year. Capital costs are calculated using the annual average value for 2018 (CEPCI = 603.1), 2008 is instead used as reference year (CEPCI = 575.5).

Finally, Equation 4 was used to determine the discounted payback time for both the scenarios:

$$IR \cdot (1 + IR)^n$$

A [redacted]

Where A are the savings minus the O&M costs (5% of the capital cost (Ail et al., 2017)), P the present worth capital cost, IR the interest rate and n the number of years to return the investment.

Two interest rates are 0 % and 2.3 % (02.05.2019) are considered.

3 Results and discussion

3.1 First scenario: dedicated char burner

The main parameter which has been used to evaluate the results is the gasification temperature, which strongly affects the production of char. The producer gas heating values measured in the real plants are used to validate the model. The model results are close enough to the measured data with relative difference ranging from 0.6 % to 5.64 % (see Figure S1).

3.1.1 Gasification temperature

Char production is correlated with gasification temperature. Ash mass flow is considered as constant since it does not react during the gasification process; on the other hand, the production of solid carbon decreases with increasing temperature, reaching the zero value in a temperature range between 669 °C and 733 °C. With higher gasification temperature, no heat could be exploited.

Figure 2 reports a sensitivity analysis which shows how the heat produced by the char combustion (evaluated by enthalpy difference) changes by varying the gasification temperature. The point where the available heat becomes lower than the total heat required (heat required to pre-heat gasification and combustion air) has been called "critical point" and it represents a technical limit for the feasibility of the plant. When the gasification temperature is lower than the one of the critical point, the heat developed by cooling the flue gas is enough to satisfy the requirements; otherwise, the heat would not satisfy the needs. The plot is similar for all the technologies and here just the one for technology A is reported. The temperatures of the critical points for the eight technologies varies between 649 °C and 714 °C. The difference in critical temperatures is due to different mass flows and equivalence ratios.

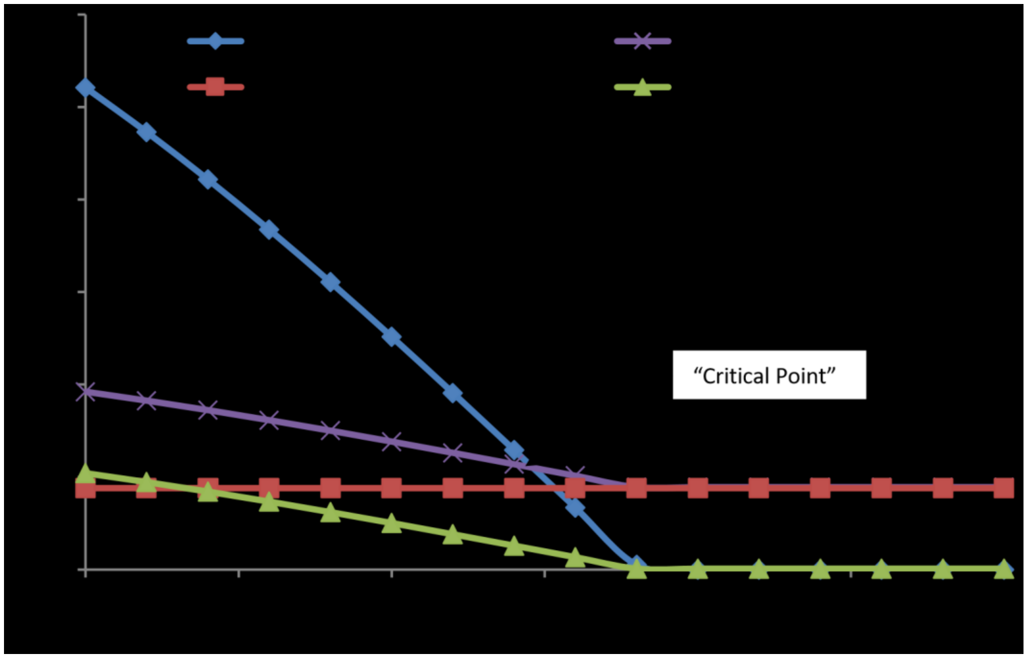


Fig. 2 Heat production varying gasification temperatures for Technology A (Flue gases heat = Exploitable heat from the flue gases; Gasification air heat = heat required to pre-heat gasification air; Combustion air heat = heat required to pre-heat char combustion air; Total heat required = sum of the heat required to pre-heat gasification and combustion air)

3.1.2 Assessment of the economic feasibility

Regarding the economic feasibility of the first scenario, char combustion would always allow a reduction in the operating costs. Know the amount of char produced by each technology (Table 1), it was possible to evaluate the "gasification savings" (GS) for all the technologies (Table 3). The owners of the gasification plants would be able to save 72% (A), 84% (B), 50% (C), 69% (D), 87% (E), 94% (F), 71% (G) and 74% (H) of the disposal costs per ton of char. The GS are linearly correlated with the amount of char produced, but there is not a correlation with the size of the plant.

This is mainly related to the difference in char production of the different technologies operating at different conditions.

Table 3 Gasification plant char disposal savings

Technology		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Electrical output	[kW_{el}/module]	45	180	150	300	50	250	440	140
Ash	[$\%wt_{dry}$]	27.84	16.08	49.52	31.50	13.34	6.49	29.16	25.64
Char	[kg/year/module]	2,982	25,218	21,977	111,293	7,811	136,980	70,000	2,000
Savings	[€/year/module]	323	3,174	1,664	11,435	1,015	19,213	7,438	223

3.1.3 Payback time

The capital cost of a char burner ($\dot{m}$=1-2 kg/h of char) currently on the market is approximately 15,000 €. This datum was obtained by an equipment vendor through personal communication. The payback time is evaluated by solving Equation 4. The char production of some technologies is out of the range for the char burner. The analysis was then performed considering more gasification or char burner modules. Table 4 reports the payback time for technology B, D and G. The payback times in the present study are extremely variable – ranging from 3 to 21 years - and depends on the char production and composition and therefore on the operating conditions of the gasifier, i.e. equivalence ratio and temperature. For this reason, three out of eight technologies (B, D and G) that can achieve a reasonable payback time, i.e. lower than 10 years, are shown. For the other technologies, the payback time is less interesting, and each plant should be investigated before the investment.

Table 4 Payback time of the char burner

Technology	IR [%]	Savings – O&M [€]	Capital cost [€]	Payback time [years]
B	0.0%	2,424	15,000	6.2
	2.3%			6.7
D	0.0%	9,935	30,000	3.0
	2.3%			3.2
G	0.0%	5,938	30,000	5.1
	2.3%			5.4

3.2 Second scenario: centralized char combustion

In this section, the main parameters (i.e. mass flows, temperatures, pressures, efficiencies), which were used to run the model relevant to the second scenario are analyzed, considering both nominal and partial load operation modes. Furthermore, an assessment of the techno-economic feasibility of this scenario is performed.

The model data of the ORC cycle were validated using experimental data (see Table S2). It is worth observing how the two data-set are in good agreement. Major deviations can be noticed on the thermal power values.

3.2.1 Operating conditions

The operating parameters were evaluated as a function of the return water temperature of the DH network, i.e. the temperature value relevant to the water stream coming back from the secondary heat exchangers of the users to the condenser of the ORC cycle. This parameter is a relevant indicator of the working conditions of the plant. An increase of the return water temperature leads to a reduction both of the MDM mass flow and of the turbine electrical output power. The change in MDM mass flow is also correlated with the variation of evaporating and condensation pressures (see Figure S2). The two curves perfectly respect the data of the reference (Prando et al., 2015). The cold side inlet temperature at the condenser increases with an increase of the condensing pressure. To avoid a temperature crossover and to keep a minimum temperature difference (5 ± 0.5 °C) between both sides of the heat exchanger, the cold side outlet temperature of the regenerator has to decrease, from its nominal condition of 195 °C (see Figure S3).

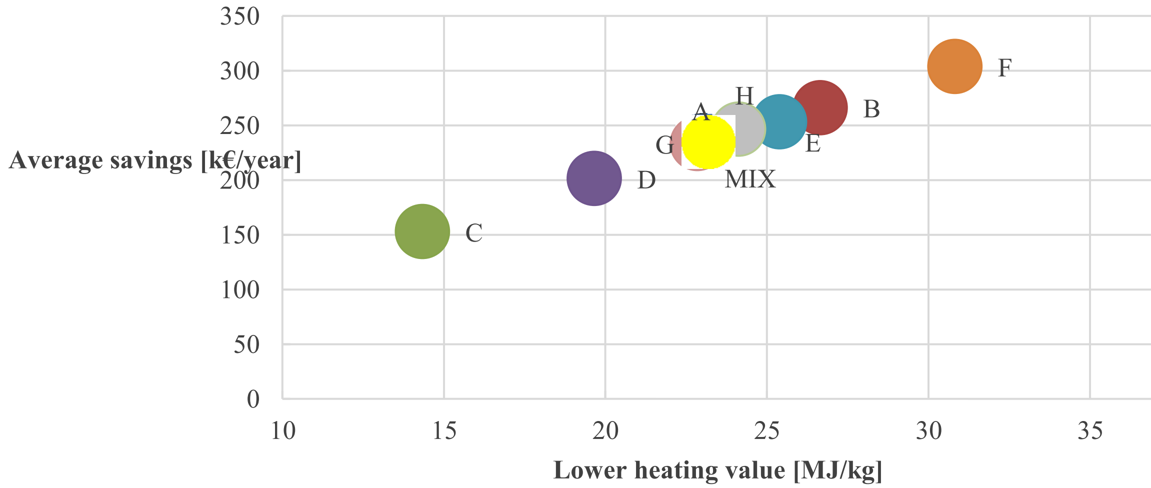
In partial load operating conditions, because of a decreased cooling effect on the ORC engine by the water of the district network, the temperature of the thermal oil after the HRVG increases and consequently also the one of the flue gases. A design specs block was then used to modulate the boiler thermal load, changing the amount of input biomass (between 0 and the nominal value of 1875 kg/h), in order to keep the temperature difference between the exiting flue gases and the return oil at 25 ± 1 °C (see Figure S4). Hence, it is highlighted in this paragraph how the model can properly predict both nominal and partial load operating conditions.

3.2.2 Assessment of the economic feasibility

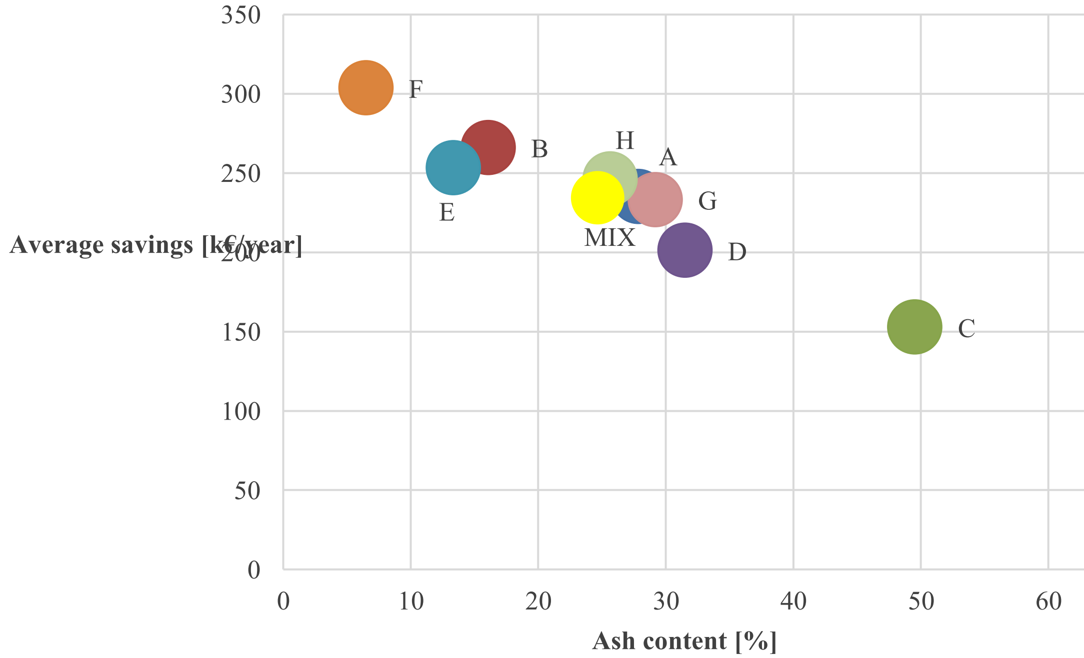
The simulation model for the second scenario is based on the idea of utilizing all the available char to substitute a fraction of the biomass input, maintaining the design operating conditions of the ORC plant. The analysis is performed considering the utilization of the whole amount of char produced in South-Tyrol in one year, which is then assumed as the design value of the char annual mass available. Thus, the mass flow rate (as kg per hours) is strictly correlated to the annual operating hours of the ORC plant. The lower the number of hours the higher the char mass flow rate. If instead the plant could work for all the year with no stops, the char mass flow rate would reach the lowest value (148 kg/h). For instance, considering 8000 hours per year as operating time of the ORC plant, which correspond to a char mass flow rate of 162 kg/h, the biomass mass flow is 1668 kg/h. This allows estimating that there could be a reduction of approximately 200 kg/h of biomass needed for the actual operation of the boiler. The amount of substituted biomass is higher than the char mass flow due to its higher heating value.

The change in biomass consumption affects the cash flow (i.e. in, net and savings) for the plant operated with just biomass or in co-combustion mode (see Figure S5). The production of electrical energy is the same, while the outgoing cash flow, composed of biomass purchase and ash disposal costs, varies. Since, in co-firing operation mode, the input biomass is lower, also the costs for biomass and for ashes disposal are lower. This increases the net cash flow, increasing the revenues. It is worth noticing that net savings do not depend on the user load, which means that for any operating conditions, there is a reduction in the operating costs. The savings related to this scenario amount to approximately 235,000 €/year. By keeping constant the char composition, this value varies linearly with the char production.

It is also interesting to evaluate how the savings may vary by changing the characteristics of the char mix. Figure 3 confirm that the savings using the char mix would be 235,000 €/year; instead, if a char with a higher heating value and lower ash content (technology F) would be used, the savings could be higher (304,000 €/year). The lowest savings are achieved with the char of technology C that has the lowest heating value and higher ash content (153 €/year).



(a)



(b)

Fig. 3 Savings as a function of a) heating value and b) ash content ($\dot{m}_{char}$ = 1300 ton/year)

The owners of the gasification plants in South-Tyrol could save on the disposal of char. They would have to pay to the ORC plant manager just the costs for the disposal of ashes and not for the carbon included in the char. The savings would be approximately as the one of Table 3. However, it should be considered that the char should be transported to a central plant and not burnt in situ. Nevertheless, the plant of Renon is in a central position in the South Tyrol region and almost all the char transporting trucks are already driving by the ORC plant.

3.2.3 Payback time

The capital cost of the ORC plant of Renon was used to evaluate the payback time of the investment for the centralized char combustion system. The data have been provided by the manager of the plant ("Rottensteiner, Hansjörg, personal communication," n.d.). The plant components considered in the calculations are relevant to the char combustion circuit, i.e. the boiler, the heat exchanger between the flue gases and the thermal oil and all the equipment used for the flue gases cleaning. The investment costs relevant to 2008 were approximately 3,100,000.0 € (i.e. cost of the whole biomass combustion system of 5.9 MW capacity). Then, using Equation 4, the current capital cost of the char combustion system was evaluated as 1,150,000 € considering a boiler with a capacity of 1.05 MW. The calculation was carried out as for the other scenario and the results are reported in Table 5.

Table 5 Payback time of the char combustion equipment ($\dot{m}_{char}$ = 1300 t/year)

IR [%]	**Savings – O&M [€]**	**Capital cost [$€_{2018}$]**	**Payback time [years]**
0.0%	177,158	1,150,000	6.5
2.3%			7.1

The results show that, given the savings previously assessed, i.e. 235,000 €/year, the payback time results to be 7.1 years (6.5 years in case of no money loan with 0% IR), which means that the system would become remunerative in an adequate time, considering an expected plant lifetime of 20 years.

3.3 Comparison between the dedicated and centralized char utilization plants The two different scenarios have both advantages and disadvantages. The dedicated char combustion plant, in which the char is immediately burnt, could maximize the savings of the gasification plant owners. In fact, this scenario would avoid the transport of the carbon, but not of the ashes. On the other hand, it should not be taken for granted that an adequate payback time could be reached also due to the low char production of some gasification plants. The economic analysis shows that just 3 out of 8 gasification technologies can achieve an adequate payback time. For technology B, D and G the payback time varies between 3 and 7 years.

Regarding the centralized char combustion plant, in which the char is transported to a single combustion plant, the savings of the gasification plant owners would be slightly lower, compared to the other scenario, due to the need to transport to the central plant also carbon and not just ashes. However, the gasification plant owners would not have to bear any capital costs. This second scenario would bring advantages also to the owners of the ORC plant. The savings are greater in this scenario and the payback time of the new equipment and installation costs that should be purchased for the char combustion is approximately 7 years.

If heat recovery is not of main concern, a simple combustion of the char (first scenario) would allow strongly reducing the disposal costs, but the payback time is highly variable. On the other hand, considering also an environmentally friendly point of view, the second scenario would represent the most interesting solution in South Tyrol and in other regions of the world. This scenario would reduce the disposal costs and could exploit energy from the char with an adequate payback time.

4 Conclusions

In this study, two process simulation models for the production of energy from biomass gasification char were developed. All the models were firstly validated with experimental results and then char combustion units (not present in the real plant) were added. The first developed model considers the local utilization of char at the gasification plant; the results show that this scenario is not always feasible. The advantages and the savings are strictly correlated to the char production and composition and therefore to the operating conditions of the gasifier, i.e. temperature and equivalence ratio. The owners of the plants could save on the char disposal costs from 50% to 94%. A payback time lower than 10 years can be achieved just for three of the eight selected technologies and it ranges from 3 to 7 years.

The second model, which considers the collection of char from the entire South-Tyrol region and its combustion in an ORC plant, exhibits also interesting results. The analysis has shown how savings can be achieved for both the owner of the ORC plant and the owners of the gasification plants, which have to dispose char. The former could save on the disposal costs, by affording those of just the ashes, after burning the char in the central plant. Instead, the owner of the ORC plant could save approximately 235,000 €/year. The time to return from the investment is approximately 7 years (6.5 years in case of 0 % interest rate). As reported before the points of main interests are that the savings are pretty much constant along the year and they do not depend on the user load or on the number of operating hours. It should be considered that these results are variable, and they depend on the estimation of the amount of char produced every year and, on its composition, (mainly heating value and ash content).

Declarations of interest: none.

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Appendix A. Supplementary material

Supplementary data to this article can be found in the attached file, named "Supplementary Material".

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