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Corresponding Author: Dr. Simone Pedrazzi, Dr.

Corresponding Author's Institution: University of Modena and Reggio Emilia

First Author: Simone Pedrazzi, Dr.

Order of Authors: Simone Pedrazzi, Dr.; Giulia Santunione, Ph.D. Student, M.Sc. Biology; Andrea Minarelli, M.Sc. Environmental Engineering; Giulio Allesina, Dr., Assistant professor

Abstract: This work discusses the advantages that can be obtained from the integration of landfill gas with biomass gasification. The case study presented consists of a landfill located in the province of Reggio Emilia, in the north of Italy. Landfill gas from municipal-waste fuels four internal combustion engines with overall nominal power of 2 MW, the electricity is sold back to the grid, while the thermal power is used for the heating of an industrial greenhouse compartment for basil production. Within the same facility, green waste is collected from the surrounding municipalities then chipped and sieved. Fine particles are disposed into a composting plant close by, while the sieved fraction is sold to the market for electricity production in large-scale boiler-based power plants. The idea here presented and discussed consists of the implementation of a gasifier to convert the sieved fraction of green waste into a syngas fuel directly on site. Syngas is blended with the landfill gas and then fed to the gas engines. In this work green waste gasification is tested in a commercial small-scale gasifier, proving that sifted green waste is a suitable fuel for this application. A specific consumption of 1.2 kg/kWh and a total electrical efficiency of 16.22% were measured. The sizing of the full-scale gasification facility is based on both the experimental results and data about the local availability of green waste. The economic return of the investment is then discussed. Finally, a further level of integration between gasification and the existing site is proposed: gasification-derived biochar is investigated as soil amendment for the on site company at the landfill that grows basil commercially. Results of 55 days in vivo tests show an increase in the biomass production of the basil of 53% compared to the control test group.

***Cover letter**

Department of Engineering "Enzo Ferrari"
University of Modena and Reggio Emilia
Via Vivarelli, 10/1 - 41125 Modena, Italy

BEELab (Bio Energy Efficiency Laboratory)
www.beelab.unimore.it

Dr. Simone Pedrazzi
Department of Engineering “Enzo Ferrari”
University of Modena and Reggio Emilia
Via Vivarelli, 10/1 – 41125 Modena, Italy
phone +39 059 205 6229, email: simone.pedrazzi@unimore.it

Professor Mohammad Ahmad Al-Nimr
Editor-in-Chief
Energy conversion and Management

Dear Professor Mohammad Ahmad Al-Nimr

I am pleased to submit an original research article entitled **Energy and biochar co-production from municipal green waste gasification: a model applied to a landfill in the north of Italy** " by Giulia Santunione, Simone Pedrazzi, Andrea Minarelli and Giulio Allesina for consideration for publication in the Energy Conversion and Management journal.

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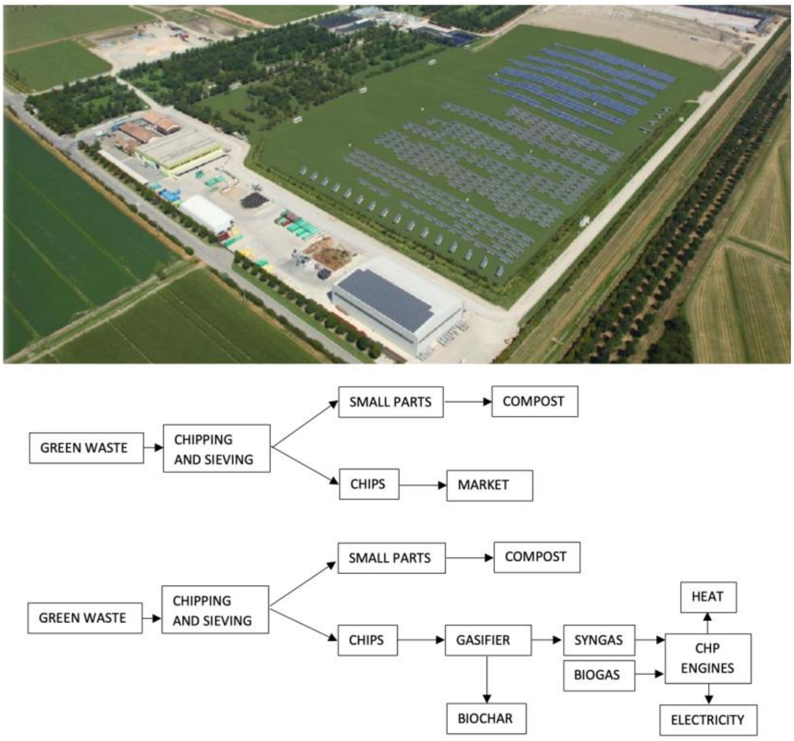

Figure 1: case study in northern Italy, and proposed solution

Furthermore, with this letter the authors certify that the content of the paper and its novelty results are the original work of the authors and it was not submitted before in this journal. With this letter all the authors mutually agree to submit their manuscript to Energy conversion and Management Journal.

We look forward to hearing from you soon.

Best regards,

M.Sc. Giulia Santunione
Dr. Simone Pedrazzi
M.Sc. Andrea Minarelli
Dr. Giulio Allesina

***Highlights (for review)**

HIGHLIGHTS

- Green waste gasification was experimentally validated through a small scale gasifier.
- Results show a gasifier electrical efficiency of 16.22% and a stable running.
- A scenario with a gasifier coupled with a landfill biogas power plant is presented.
- The full scale gasifier cost is 5 M€ and the investment payback time is 6 years.
- Gasification biochar has proven to be an excellent fertilizer for basil growth.

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Energy and biochar co-production from municipal green waste gasification: a model applied to a landfill in the north of Italy

Simone Pedrazzi*, Giulia Santunione, Andrea Minarelli, Giulio Allesina

BEELab (Bio Energy Efficiency Laboratory, Department of Engineering “Enzo Ferrari”, University of Modena and Reggio Emilia, Italy)

* Corresponding author: Simone Pedrazzi, Department of Engineering “Enzo Ferrari”, Modena Italy. Mail: simone.pedrazzi@unimore.it

Abstract

This work discusses the advantages that can be obtained from the integration of landfill gas with biomass gasification. The case study presented consists of a landfill located in the province of Reggio Emilia, in the north of Italy. Landfill gas from municipal-waste fuels four internal combustion engines with overall nominal power of 2 MW, the electricity is sold back to the grid, while the thermal power is used for the heating of an industrial greenhouse compartment for basil production. Within the same facility, green waste is collected from the surrounding municipalities then chipped and sieved. Fine particles are disposed into a composting plant close by, while the sieved fraction is sold to the market for electricity production in large-scale boiler-based power plants. The idea here presented and discussed consists of the implementation of a gasifier to convert the sieved fraction of green waste into a syngas fuel directly on site. Syngas is blended with the landfill gas and then fed to the gas engines. In this work green waste gasification is tested in a commercial small-scale gasifier, proving that sifted green waste is a suitable fuel for this application. A specific consumption of 1.2 kg/kWh and a total electrical efficiency of 16.22% were measured. The sizing of the full-scale gasification facility is based on both the experimental results and data about the local availability of green waste. The economic return of the investment is then discussed. Finally, a further level of integration between gasification and the existing site is proposed: gasification-derived biochar is investigated as soil amendment for the on site company at the landfill that grows basil commercially. Results of 55 days in vivo tests show an increase in the biomass production of the basil of 53% compared to the control test group.

Keywords: landfill, green waste, gasification, combined heat and power, biochar, basil.

1. Introduction

Green waste is an unavoidable by-product produced by municipalities, it is obtained from the maintenance of public green areas, municipal parks and forestry [1]. Together with other municipal waste material, it represents one of the urgent challenges to face for increased sustainability of our societies [2, 3]. In this context, the utilization of the green waste for bio-energy production is a promising solution [4, 5]. Green waste consists of: dead trees and stomps, pruning of trees and shrubs, leaves, grass clippings and dirt [6, 7]. Due to its low energy density and its high moisture content, it is usually collected and sent to composting plants, landfill etc. [8]. In all the cases above, the disposal of green waste represents expenditure for the municipality. Furthermore the composting process, a competitor technology to the energy conversion, releases Volatile Organic Compound (VOC), methane and carbon dioxide that contributes to the atmospheric pollution and climate change [7-11]. The amount of green waste collected in Italy every year is more than significant; a study regarding the region of Emilia Romagna estimates a production of about 400,000 tons/year, leading to a *pro capite* amount of 86 kg/year [12]. The green waste management issue also affects highly inhabited areas, i.e. Rome produces about 82,000 tons of green waste every year [13]. Citing the World Energy Council 2016: “the waste management sector faces a problem that it cannot solve on its own. The energy sector, however, is considered to be a perfect match, because of its need to continuously meet a growing energy demand.” [14].

The market offers several technologies capable of converting organic biomass into energy efficiently. Thanks to higher ideal conversion efficiency, gasification stands out against the other thermochemical technologies. Gasification consists in the thermal decomposition of the biomass into a fuel gas (syngas) through under-stoichiometric reactions [15, 16]. As common practice, the gas is cleaned from pollutants (particulates, tars, soot) and then burned into internal combustion engines for combined heat and power production [17, 18]. Gasification of ligno-cellulosic biomasses produces sustainable energy as well as a valuable by-product known as biochar with good soil amendment properties [19-23]. Biochar is defined as a carbon-rich product produced through thermal degradation [24, 25]. Because of its high porosity, biochar can hold water and release it to the plant during periods of water scarcity [26, 27]. Therefore, the production of biochar, in combination with its storage in soil, has been suggested as a promising way to capture and store atmospheric CO_2 [28,29].

Even though biomass gasification is an efficient technology, it has some disadvantages such as restricted fuel flexibility and high cost. These issues become more significant in large industrial applications. An accurate gasifier design and complex control strategies can nullify the risk of power plant shutdowns and decrease the Operation Expenditures (OPEX).

This work focuses on the analysis of a virtuous solution for green waste energy conversion in existing waste management sites. The proposed system integrates the existing facilities refining the economical sustainability with the further benefit of biochar production for soil improvement. Currently, the best practice for green waste management consists of its collection and chipping in order to reduce its volume. The resulting biomass is sieved using different methods. The fine fraction has a high content of dust, rock and bark and it is disposed of in landfills or in composting plants. The sifting process selects biomass with a high enough quality to be sold to the market as fuel for Combined Heat and Power (CHP) combustion power plants. The core idea of this work consists on the virtuous approach that can arise from the use of gasification within existing green waste management sites. The idea is based on the green waste chipping and sieving processes within existing landfill sites. The sieved biomass with low quality is disposed of in compost plants and the remaining biomass is used as fuel in a gasifier reactor to make biochar and syngas. Syngas is filtered and mixed with the landfill gas; the gas mixture is used as fuel in the existing CHP engines of the landfill power plant. In this way, CHP gas engines will produce more power compared with the conventional scenario, furthermore syngas will compensate for the decrease of the methane content of landfill gas throughout the years [30, 31]. This advantage increases the economical profitability of the landfill.

Without a proper distributed heating network, the heat produced by the CHP modules in landfills is hard to exploit in a proper way, especially because landfill sites are usually built far from those urbanized areas that can benefit from the heat production. In this paper, the gasification of sieved green waste is modelled and applied to a case study where the heat released by the engines is used in an efficient way. The company that manages the landfill is named “S.A.B.A.R.” and it is located in the north of Italy close to the city of Novellara, in the province of Reggio nell’Emilia. Here, four IC engines use landfill gas to produce about 2 MW of electrical power and 2.5 MW of thermal power. A substantial fraction of this thermal power, about 1.8 MW, is used to heat 2 greenhouses with a total surface area of about 4,500 m^2. Basil is cultivated in the greenhouses. Currently, the company manages public and private green waste collected from the surrounding municipalities. After chipping and sieving it, the fine part of the green waste is exploited in a composting plant close to S.A.B.A.R. and the remaining part is sold on the market for about 5 €/ton.

In this work, gasification of green waste is validated through experimental tests in a small-gasifier equipped with an IC engine. Results from experimental tests were used to discuss the economical advantages of landfill revamping through the coupling of a gasification stage to the existing landfill gas power plant. Finally, basil growth tests were used to prove the further advantages of gasification biochar usage as soil fertilizer.

2. Material and methods

2.1 Landfill description

S.A.B.A.R. is a multi-utility company owned by several municipalities in the province of Reggio nell’Emilia, in the north of Italy. Since 1983, S.A.B.A.R. operates the landfill depicted in Figure 1. Three photovoltaic power plants are placed on the closed landfill digs for a total installed peak power of 2.15 MW. In 2017, S.A.B.A.R. collected about 42000 tons of non-recycled waste coming from the municipalities in the immediate vicinity. In addition, 37989 tons of green waste was processed in the same year [32]. The green waste collected is composed of 32% wt. grass clipping and leaves, and 68 % wt. wood prunings and wood logs. The incoming green waste is discharged on a concrete platform. Material handling grapples load the green waste into the hopper of the chipping facility. The chipper is equipped with a sifter with 20 mm hole screen. The biomass that has a dimensions between 20 and 150 mm constitute the valuable material, while the fine particles with dimensions below 19 mm are disposed of in the composting plant. In 2017, about 18294 tons of wood chips with a moisture content of 39% were available on a yearly basis [32]. Currently, this biomass is sold to companies that operate biomass combustion power plants, which are, on average, 200 km from S.A.B.A.R. The cost and the environmental impact of the transport is massive. A study regarding the transport of forest chips and forest industry by-products with large truck-trailers in Finland reports a transporting cost that ranges from 4 to 5 €/m^3 for a transport of 200 km [33]. Considering a bulk density of 300 kg/m^3 for the wood chips at 40% of moisture [33], the cost of transport of the S.A.B.A.R. wood chips ranges from 13.3 to 16.6 €/ton. Therefore, the total cost of the woodchips ranges from 18.3 to 21.6 €/ton considering the raw biomass cost of 5 €/ton. This value is nevertheless viable for the power plant owners because “high quality” dry woodchips cost up to 120 €/ton [34].

Figure 1: S.A.B.A.R. landfill

The technical specs of the engines are reported in Table 1. The landfill gas data reported here are the average values that refer to 2015. The total electrical and thermal power output is calculated as follows:

$$P_{el} = \dot{V}_{gas} LHV_{gas} \eta_{el} \qquad (1)$$

$$P_{th} = \dot{V}_{gas} LHV_{gas} \eta_{th} \qquad (2)$$

Where P_{el} [kW] is the electrical output, $\dot{V}_{gas}$ [Nm^3/h] is the landfill average gas production, η_{el} [%] is the electrical efficiency of the unit, LHV_{gas} [MJ/Nm^3] is the landfill gas lower heating value and η_{th} [%] is the thermal efficiency of the unit. The engine's cooling circuit is connected to a heat exchanger that is connected to a district heating line and to the heating circuit of the greenhouses. Not the entire thermal output of the engine is used to heat the greenhouses, in fact part of it is used in a district heating line serving the landfill facilities. During the cold season, the maximum heating load of the greenhouses, in order to have a constant internal temperature of 30 °C is about 1.8 MW and it is calculated as follows:

$$\dot{Q}_{gh} = \dot{m}_{H_20} c_{p,H_20} (T_{in} - T_{out}) \qquad (3)$$

where $\dot{Q}_{gh}$ [kW] is the maximum heating load of the greenhouses, $\dot{m}_{H_20}$ [kg/h] is the water mass flow of the heating circuit of the greenhouses (77500 kg/h), c_{p,H_20} [J/(kg K)] is the water specific heat (4.186 J/(kg K)), T_{in} [°C] is the temperature of water at the inlet of the heating circuit of the greenhouses and T_{out} [°C] is the temperature of water at the outlet of the heating circuit of the greenhouses. The landfill gas production decreases every year because today the landfill is full and the existing waste fermentation has a downward trend. Figure 2 reports the calculated flow of produced and usable landfill gas from 1983 to 2035 and the measured flow from 1996 to 2013 [36]. The measured flow is lower in respect of the calculated flow, this phenomenon was probably due to the introduction of waste sorting in the waste disposal process. In fact, with this method, the amount of organic waste to the landfill is negligible and consequentially the landfill gas production is low. Therefore, the model estimates that the landfill gas production will end in 2035 and, looking at the measured production, this deadline will happen earlier. For this reason, the substitution of landfill gas with another gaseous fuel is mandatory to assure the operability of the CHP engines and greenhouses. Syngas from green waste gasification or biogas from digestion of anaerobic organic waste can be two valuable alternative fuels. This paper introduces green waste gasification coupled with landfill anaerobic digestion. Figure 3 compares the status quo (A) and a new scenario with a gasification stage (B). Here the syngas produced from green waste is used as fuel in CHP engines together with landfill gas.

Table 1: CHP engines and landfill gas characteristics

Engine type	GE Jenbacher JGS 320 [35]
Max. electrical output [kW]	1067
Max. power input [kW]	2608
Thermal efficiency [%]	45.2
Electrical efficiency [%]	40.9
Total efficiency [%]	86.1
Landfill gas methane content [% vol.]	47.6
Landfill gas production [Nm^3/h]	1200
Landfill gas lower heating value [kWh/Nm^3]	4.43
Landfill gas power input [kW]	5316
Total electrical output [kW]	2173
Total thermal output [kW]	2401

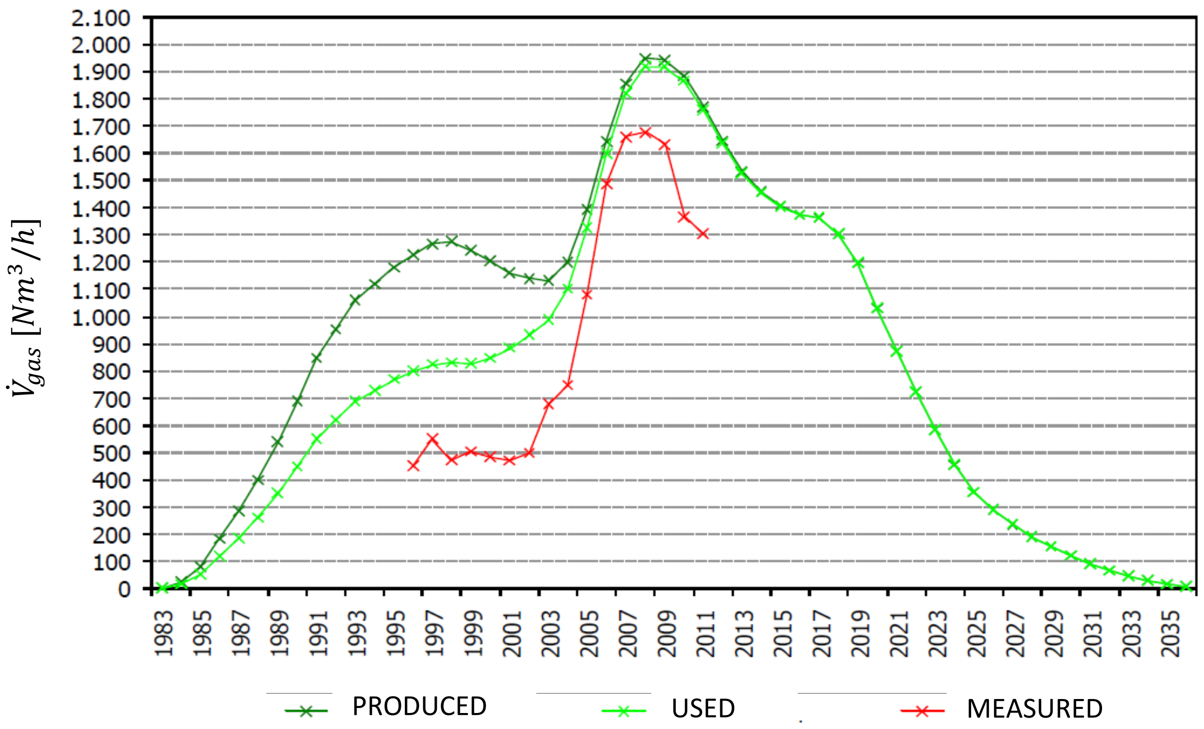

Figure 2: Modelled landfill gas production and comparison with measured data [36]

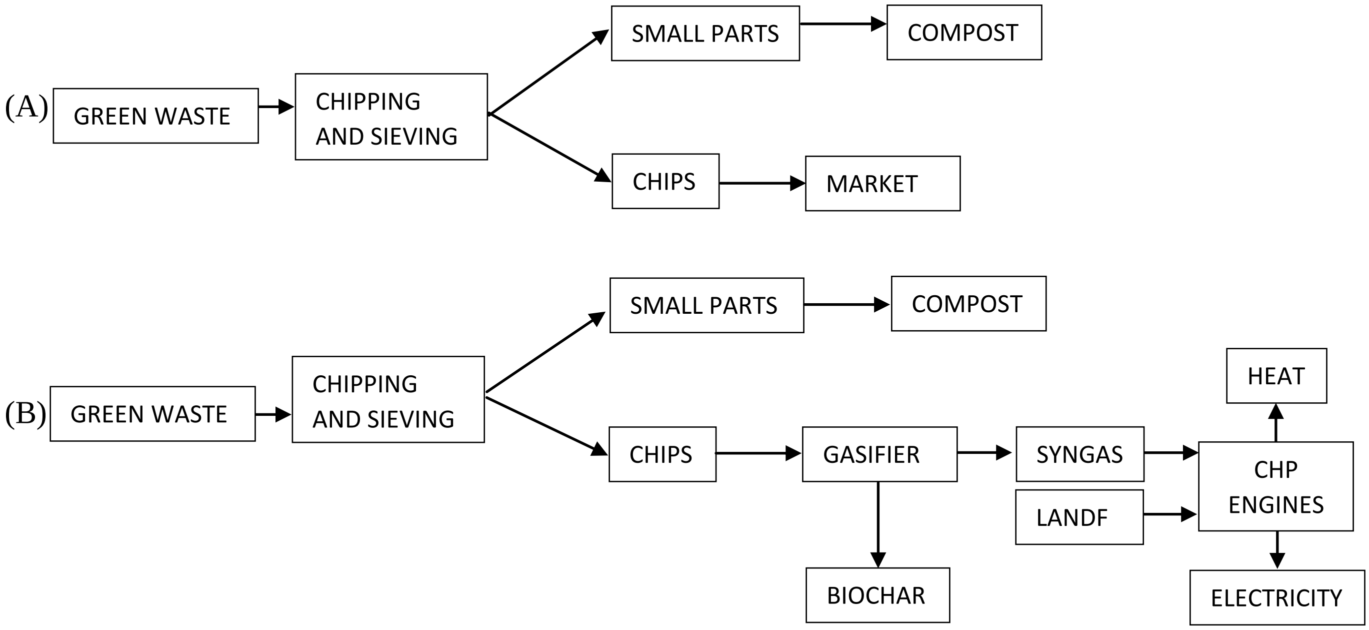

Figure 3: (A) S.A.B.A.R. actual operation of green waste; (B) S.A.B.A.R. alternative operation of green waste

2.2 Municipal green waste gasification

In order to properly assess the feasibility of green waste conversion into commercial gasifiers, 250 kg of chipped green waste with a moisture content of 40% was sieved and dried in an industrial dryer. Figure 4 reports the green waste before and after these processes. Approximately 100 kg of dry wood chips was collected. Concerning wood chips particle size after sieving, the equivalent wood chips class is P45A according with the standard UNI EN ISO 14961-1. Ash content of the biomass was evaluated burning a biomass sample on a furnace at 550 °C for 4 hours as suggested by the ASTM E1755 standard. Biomass moisture content was calculated according to UNI EN ISO 18134-1. In addition, an elemental analysis was performed using a FLASH 2000 Organic Elemental CHNS Analyzer [37]. Table 2 summarizes results of these analyses. The higher heating value of the dry biomass $HHV_{bio,dry}$ [MJ/kg] is calculated through the Channiwala and Parikh correlation [38]:

$$HHV_{bio,dry} = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1ASH \tag{4}$$

where C [%wt.] is the biomass carbon content, H [%wt.] is the biomass hydrogen content, S [%wt.] is the biomass sulphur content, N [%wt.] is the biomass nitrogen content, O [%wt.] is the biomass oxygen content and ASH [%wt.] is the biomass ash content. These data is collected from the analysis of biomass sample that is completely dry. The composition of the collected green waste is similar to the composition of wood chips from urban prunings reported in the ECN Phyllis biomass and waste database [39]. Ash content is higher in green waste than in pure wood due to the presence of bark in the biomass collected in the site. The higher heating value of green waste is slightly lower than the higher heating value of pure wood, however it is still high enough to test this biomass in the gasification regime.

Table 2: Green waste characterization in dry conditions

Biomass composition in dry conditions			
	Case study green waste	Phyllis green waste [39] item #3342	Phyllis pure fir wood [39] item #239
Carbon content C [% wt.]	46.93	47.5	50.36
Hydrogen content H [% wt.]	5.85	5.74	5.92
Sulphur content S [% wt.]	0	0	0
Nitrogen content N [% wt.]	0.94	0.22	0.05
Oxygen content O [% wt.]	41.38	41.57	43.39
Ash [% wt.]	4.9	4.97	0.28
Moisture after drying M [% wt.]	11.1	11.08	/
Higher Heating Value in dry conditions [MJ/kg]	18.8	19.68	19.78

Figure 4: Green waste sample before and after the sieving and drying processes

To perform the green waste gasification test, a pilot scale, All Power Labs PP30 fixed bed gasifier [40] was used. The schematic of the system is depicted in Figure 5. This particular gasifier can be fed with agricultural and forestry waste biomasses with a moisture content up to 30%. It consists of two main different parts: a gas making sub-system and a power generation unit. The gas making sub-system consists of a hopper with a volume of approximately 0.3 m^3, a downdraft single-throat reactor and a drum filter. The biomass is manually loaded into the hopper and conveyed into the reactor by an auger. A sensor on the top of the reactor controls the auger feed rate. The syngas that is produced leaves the reactor and runs into a heat exchanger that transfers heat to the combustion air of the engine. The syngas produced contains two main species of pollutants: particulate matter and tar. A cyclone placed downstream from the reactor collects most of the particulate while the drum filter removes the remaining dust and tar. Once filtered, the gas flows into the Ashok Leyland 4.0-liter spark ignition engine, which is connected to a Marathon 284CSL1542 generator [40]. The power generation system is capable of a maximum of 22 kW of electrical power at 50 Hz. However, during the gasification test, the power output was kept at about 15 kW. This value was chosen far enough from the maximum power output in order to guarantee sufficient stability of the engine operation, also during feedstock refuelling. The dry biomass consumption $\dot{m}_{bio,dry}$ [kg/h] and the total electrical energy produced E_{el} [kWh] are measured in order to calculate the specific biomass consumption $s_{bio,tot}$ expressed in kg/kWh. Since the gasifier is not provided with a level sensor in the hopper, the biomass consumption was calculated by measuring its level at the beginning of the test and weighing the biomass needed to reach the same level at the end of the test. The volumetric flow rate of the syngas $\dot{V}_{syngas}$ [Nm^3/h] was indirectly calculated according to Equation 5 by measuring the gasification airflow entering the reactor through an anemometer. The N_2 content of the syngas as well as its total composition were measured with a Pollution Micro GCX gas chromatograph [41]. All the samples were drawn after the syngas filtration stage. The gasification and total efficiency were calculated according to Equations 6 and 7.

$$\dot{V}_{syngas} = \dot{V}_{air} \cdot \frac{0.781}{N_2} \tag{5}$$

$$\eta_{\text{gas}} = \frac{\dot{V}_{\text{syngas}} \cdot HHV_{\text{syngas}}}{\dot{m}_{\text{bio,dry}} \cdot HHV_{\text{bio,dry}}} \tag{6}$$

$$\eta_{\text{tot}} = \frac{3.6\, P_{\text{el}}}{HHV_{\text{bio,dry}}\, \dot{m}_{\text{bio,dry}}} \tag{7}$$

Finally, the higher heating value of the syngas HHV_{gas} [MJ/Nm^3] was calculated with the following equation:

$$HHV_{syngas} = \frac{12.75H_2 + 12.63CO + 39.72CH_4}{100} \tag{8}$$

where H_2 [% vol.] is the hydrogen volumetric fraction of the syngas fuel, CO[% vol.] is carbon monoxide volumetric fraction of the syngas fuel and CH_4 [% vol.] is the methane volumetric fraction of the syngas fuel.

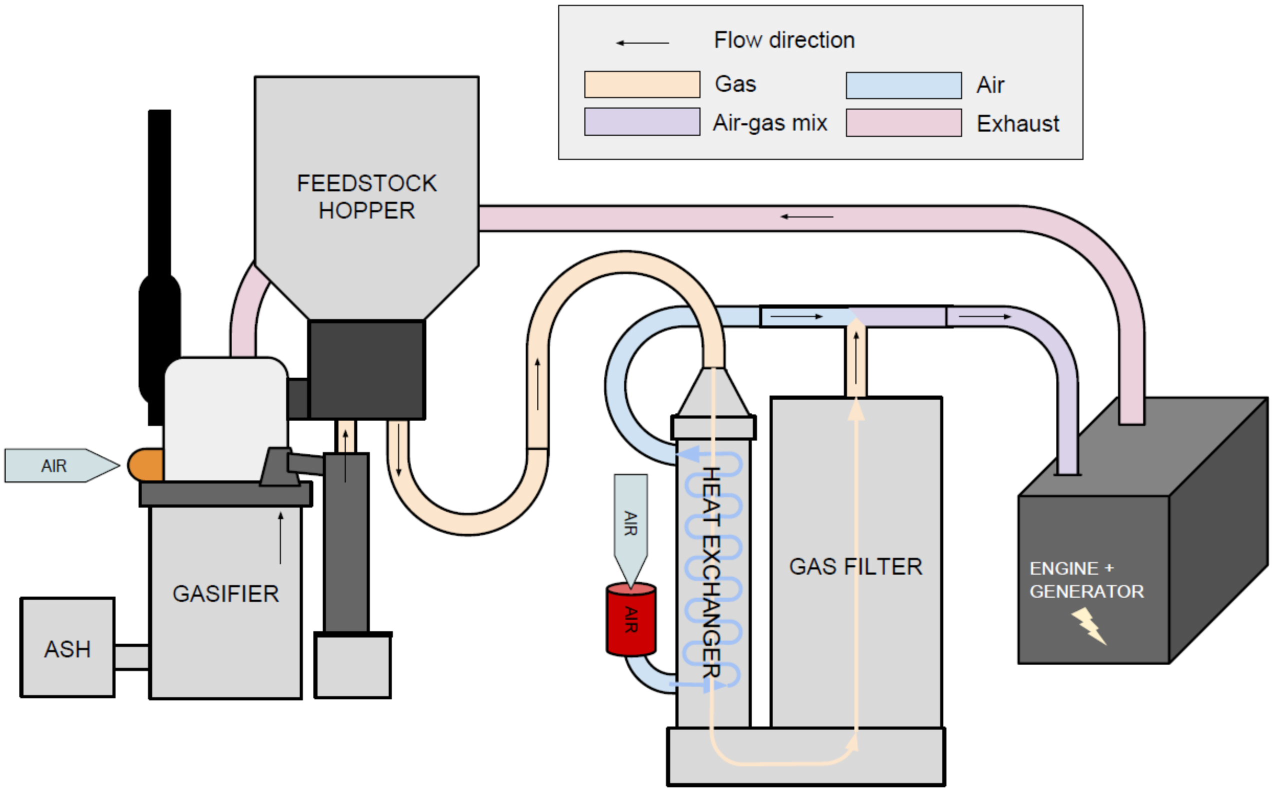

Figure 5: Schematic of the All Power Labs PP30 gasifier system [33].

2.3 Plants growth test with biochar

Beyond heating and power, the small scale All Power Labs PP30 gasifier produces a valuable by-product from green waste, represented by biochar. Its characterization is reported in a previous work [42]. Biochar BET surface is 394.4 m^2/g, real density is 2.1254 g/cm^3 and the XRF analysis indicates the presence of K, Ca, Fe and Sr in the char. In this work, an *in-vivo* experimental study was set up to investigate the effects of biochar on soil application compared to the effects of normal soil and from the organic matter of urban waste used, compost. The growth rate of the plant species *Ocimum basilicum* related to three different substrates type were considered: standard soil, soil mixed with 30% wt. of compost from organic fraction of municipal waste, soil mixed with 30% wt. of woodchip biochar. Initially, 5 seeds were planted in each terracotta. 5 pots for each substrate type were filled and put in a greenhouse equipped with red and blue LED lights. The Photosynthetically Active Radiation (PAR) was measured with a PAR sensor, model HY-MD-D 169-S. In the greenhouse, the average PAR measured was 200 ± 20 µE/m^2/s and it was lit 12 hours per day in the germination period of the shoots (4 weeks), afterwards the light period was extended to 14 hours per day. The study was carried out indoors from February to April at the Department of Engineering “Enzo Ferrari” in Modena, Italy. The experiment lasted 55 days. The relative humidity (RH) and temperature (T) of the greenhouse were maintained automatically at 30-70% and 18-27°C by an *Arduino-based* circuit.

2.4 Characterization of plants

The *O. basilicum* culture was used to evaluate the differences among substrates types and their influence on biomass production. The germination rate in each pot was checked and the growth velocity of the plants was recorded with a Nikon D5000 camera. The height of each seedling was measured with calipers. The produced biomass weight was measured using a Radwag PS360/C/2 scientific grade scale; the precision of the instrument is 0.001 g. The results include the data from 5 repeated test for each substrate type and were processed with statistical tools: the mode, average, standard deviation and analysis of variance (ANOVA) were calculated to obtain representative and comparable indicators among the different groups of pots.

3. Results and discussion

3.1 Green waste gasification

The gasification test of the treated green waste lasted about 4 hours. After half an hour of start-up with fir wood chips, 100 kg of sieved and dried green waste was loaded into the hopper. The electrical power production was set up at 15 kW to have a significant test duration and run stability. The electrical power was dissipated through a load-bank, the thermal power (about 20 kW) was used in a dryer to reduce the moisture of the fir wood chips. After about 1 hour of gasification with green waste only, two syngas samples were analysed in a gas chromatographer in order to evaluate the gasification behaviour. Results of gas chromatography and of the gasification tests are reported in Table 3. The gas chromatography analysis was done on two dried syngas samples because the water in the gas can damage the gas chromatography apparatus. The water was removed cooling the syngas to ambient temperature and using an adsorbent medium (silica gel). Water in the gas influences the engine performance, however in the Power Pallet water condensation in the gas line was prevented by setting up the temperature of the gas to about 60 °C, for this reason the evaluation of the syngas water content is not necessary. Results showed a minimum variability of the gas components and the average higher heating value of the gas was 6.55 MJ/Nm^3. This value is in line with syngas heating value of downdraft fixed bed reactors [43]. It is therefore possible to affirm that the gasification of green waste was successful in the All Power Labs gasifier. In addition, the biomass specific consumption was about 1.2 kg of dry green waste per kWh of electricity produced, this value is a little higher than the biomass consumption given by the manufacturer (1 kg/kWh). This is probably due to the high ash content of the biomass. The calculation of the gasification efficiency is described in Equation 6. It is the ratio between the chemical energy in the gas and the chemical energy in the fuel biomass. Given the above-mentioned Equation 6 it is possible to deduce the effect of a different gasifier design. The scaled-up solution described in this work uses the results of the pilot-scale experimental analysis as basis. A full-scale reactor, specifically designed for green waste management, might not have the same efficiency recorded in the preliminary tests on the PP30 gasifier. An increase in the efficiency leads to a linearly increase of the power production for a fixed amount of fuel managed. Table 3 also reports the specific syngas production s_{syngas} [Nm^3/kg] calculated dividing the syngas flow rate by the dry biomass consumption. This data is useful to estimate the volume of syngas obtainable from a given amount of biomass.

Table 3: Dry syngas composition and gasification test results

Syngas component	**Sample 1**	**Sample 2**	**Average**
Hydrogen H_2 [% vol.]	18.7	18.0	18.35
Nitrogen N_2 [% vol.]	40.0	40.6	40.3
Carbon monoxide CO [% vol.]	25.3	26.1	25.7
Carbon dioxide CO_2 [% vol.]	10.3	9.4	9.85
Methane CH_4 [% vol.]	2.5	2.3	2.4
HHV_{syngas} [MJ/Nm^3]	6.6	6.5	6.55
Air flow rate $\dot{V}_{air}$ [Nm^3/h]	15.31	15.30	15.305
Syngas flow rate $\dot{V}_{syngas}$ [Nm^3/h]	29.91	29.45	29.68
Dry biomass consumption $\dot{m}_{\mathrm{bio,dry}}$ [kg/h]	-	-	18.18
Equivalence ratio ER	0.1928	0. 1927	0.19275
Specific syngas production s_{syngas} [Nm^3/kg]	1.645	1.620	1.632
Gasifier average hearth temperature [K]	-	-	900
Gasifier average reduction temperature [K]	-	-	1200
Gasification cold efficiency η_{gas} [%]	-	-	57.95
Electrical power production P_{el} [kW]	-	-	15
Total electrical efficiency η_{tot} [%]	-	-	16.22
Biomass specific consumption $s_{bio,tot}$ [kg$_{\mathrm{bio,dry}}$/kWh]	-	-	1.2

3.2. Green waste gasification applied to the S.A.B.A.R. landfill

The pilot test demonstrates that a fraction of the managed green waste can be successfully used as fuel in gasification after a proper pre-treatment. Results of the scaled tests are the basis for sizing the full-scale idea depicted in Figure 6.

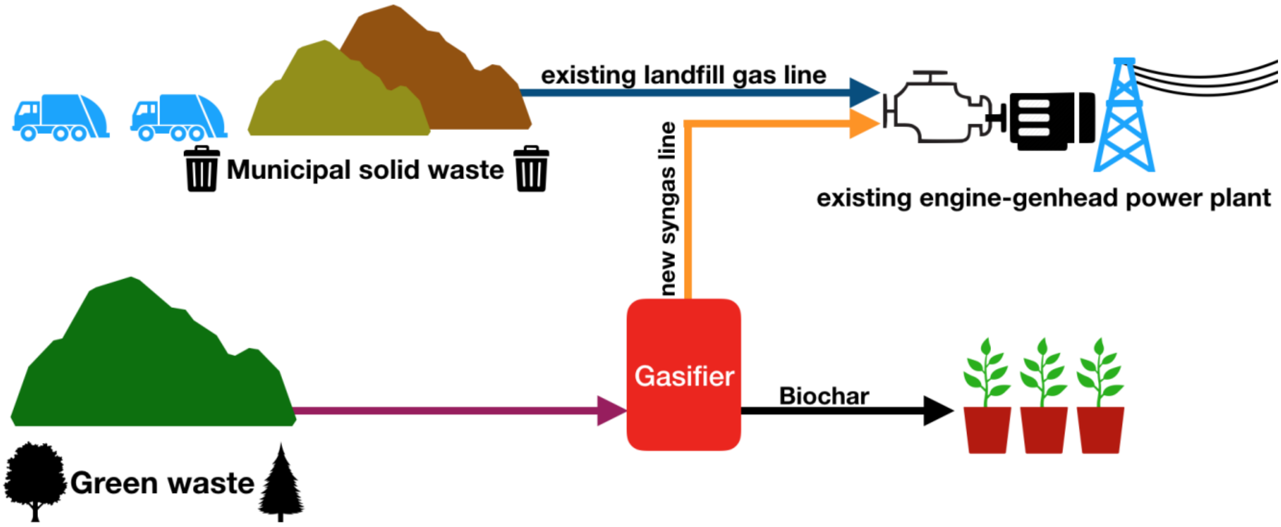

Figure 6: Landfill gas power plant coupled with green waste gasification system

Starting from the expected biomass amount, a suitable gasifier needs to be sized. The main results regarding biomass availability, gasifier characteristic and integration with CHP engines are reported in Table 4. Two scenarios are here reported considering low biomass availability (2013 data) [44] and high biomass availability (2017 data) [32]. About 8113 tons of dry green-waste-derived wood chips were available in 2013 and the value peaked at 11160 tons in 2017. The gasifier was sized considering 7500 hours/year of operation and the 2017 biomass availability. A maximum gasifier thermal power input of 7.77 MW was calculated. Therefore, the syngas produced by gasification has a maximum chemical power of 4.5 MW. The decay in the anaerobic digestion processes can be outlined by the production trend reported in Figure 2. The original power plant was capable of 4268 kW of power, according to the tech data reported in Table 1. The last landfill reading of anaerobic digestion gas production shows a maximum electrical power production of 2173 kW, less than half of the nominal power. The syngas produced through gasification can partially balance out the descending landfill gas productivity, raising the total power production from 2173 kW to 4016 kW when using landfill gas + syngas, in the same way the thermal power will rise from 2401 kW to 4438 kW as derived from 2017 biomass availability.

Gasification of green waste will substitute the landfill gas flow reduction and it is also more profitable in comparison to the sale of green waste. In fact, S.A.B.A.R. benefits from the selling of the electrical energy produced through the “Certificati Verdi” feed-in-tariff mechanism [45]. The profit from 1 MWh of electricity produced from landfill gas is 79.16 €. Using the gasifier sub-system, an increase of the produced electrical energy of about 13822.5 (9862.5) MWh/y is achieved considering 2017 (2013) data. The profit is 1094189 €/year considering 2017 data and it is 780715 €/year considering 2013 data, more than ten times higher than the sale of the biomass on the market which has a profit of about 66500 €/year. However, the investment and O&M costs of the gasifier need to be taken into account. Capital Expenditures (CAPEX) of a full scale gasifier system is about 4000 € for every kW of nominal electrical power [46], therefore a power plant sized for maximum the biomass availability has a 1843 MW (Table 3) of nominal electrical power would have a cost of 7.37 M€. However, it is fundamental to underline that, due to the uniqueness of the S.A.B.A.R scenario no engines are needed for the gasifier because the same existing engines fuelled by landfill gas will be exploited. From this consideration, a cost of the gasifier system of 5 M€ is taken into account. O&M cost of standard gasifiers is about 0.02 €/kWh [46], in this case an annual O&M cost of about 276450 €/year is considered in the scenario with 2017 data, the value decreases to 197205 €/year considering 2013 data. With these assumptions, an economical Net Present Value (NPV) analysis was performed [45]. The following formula was used to calculate the NPV value at the n-th year as the sum of the discounted cash inflow in the year from 0 to N:

$$NPV = \sum_{n=0}^{N} \frac{(I_{cv} - I_{O\&M})}{(1 + WACC)^n} - I_o \tag{9}$$

where $WACC$ is the Weighted Average Cost of Capital [47]; I_{cv} [€] is the value of the annual subsidy for the electricity produced through renewable sources; $I_{O\&M}$ [€] is the annual O&M cost of the gasifier and I_o [€] is the initial investment. Figure 7 shows the NPV analysis of the investment considering 2013 and 2017 data, N = 15 years and the WACC equal to 1% and 5%. The choice of N derives from “Certificati Verdi” subsidies regulation, WACC limits are suggested by literature [45]. The payback time of the gasifier investment is acceptable. In fact, in the worst case the Return Of Investment (ROI) is about 11 years with WACC = 5% and minimum biomass availability (recorded in 2013), while the best case is achieved with WACC = 1% and maximum biomass availability, the respective ROI is about 6 year. A further important result of the NPV analysis is the Internal Rate of Return (IRR) defined as the value of WACC that nullify the NPV value. The IRR values range from 7.97% (worst case) to 14.9 % (best case): a reasonable range for this kind of investments [48]. In addition, the system provides at least 160 tons of biochar every year. Part of it can be used as soil enhancer for the basil greenhouse cultivations, the remaining part can be sold to the market as biochar with a profit of about 1-2 €/kg [49]. Selling of biochar is not considered in the financial analysis because the effective production depends on the full scale gasification technology.

Table 4: Results regarding green waste gasification and integration with landfill gas

Annual biomass availability	**2013** [44]	**2017** [32]
Wet biomass amount at 39 % moisture [ton]	13300	18294
Dry biomass amount [tons]	8113	11160
Dry biomass heating value [MJ/kg]	18.8	18.8
Gasifier characteristics		
Annual working hours [hours]	7500	7500
Biomass thermal power input [kW]	5649	7771
Syngas total volume V_{syngas} [m^3]	13240416	18213120
Syngas flow rate $\dot{V}_{syngas}$ [Nm^3/h]	1765.39	2428.41
Syngas thermal power P_{syngas} [kW]	3212	4503
Annual biochar production [tons]	162.26	223.20
Power production from the CHP engines		
Gas power input (landfill gas + syngas) [kW]	8528	9819
Electrical output [kW]	3488	4016
Electrical output increase [kW]	1315	1843
Thermal output [kW]	3855	4438
Thermal output increase [kW]	1454	2037

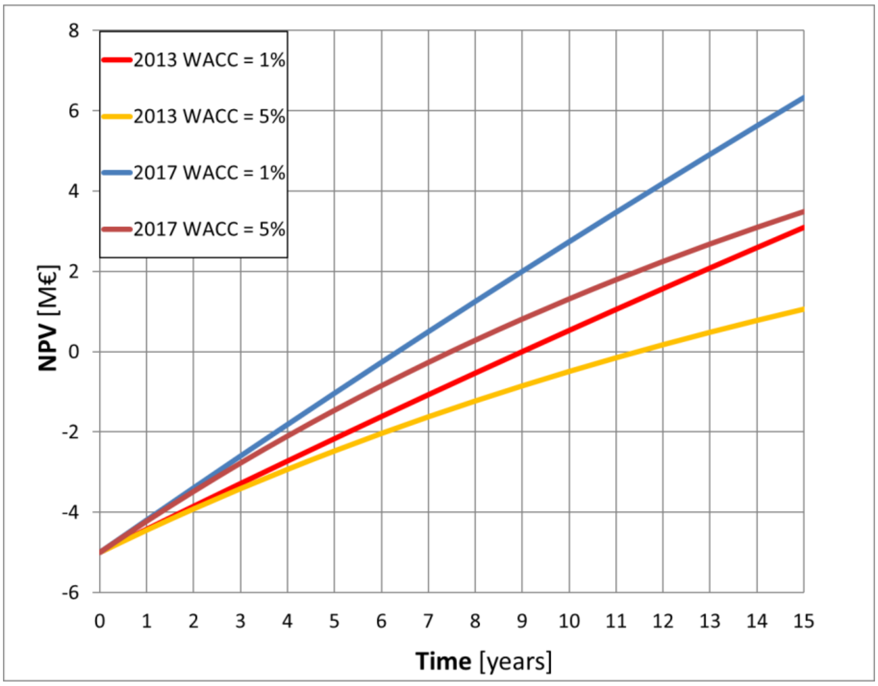

Figure 7: Net present value analysis of the gasifier investment

3.3 Biomass growth rate

To evaluate the biochar enhancing power on basil compared to other substrate types, some growth rate parameters were measured. Basil shoots were harvested after a growth period of 55 days. The germination rate of the seeds, the height and weight (fresh and dry) of the 3 main shoots for each pot were measured, in order to evaluate which substrate type had the best performance on biomass production. Parameter data was collected from 5 pots for each of the 3 substrate types (Soil, Biochar and Compost). Mean values of 5 repeated tests for each substrate type are shown in Table 5 and Figure 8. The dry weight of the plant was obtained by drying the seedlings in a heater at 60 °C for 24 hours [50]. The fresh basil biomass production in the biochar substrate is significantly higher (*p*-value, $p < 0.05$) than in the standard soil and compost. If we evaluate the dry weight, biochar biomass is comparable with soil biomass production, but not with the dry weight of compost biomass, which is significantly lower than biochar ($p < 0.05$). The height of the biochar and control shoots is comparable: 6.07 ± 1.33 cm is the mean value height for biochar seedlings and 6.07 ± 1.42 cm is the mean value height for the control seedlings. The height of the compost plants has a mean value of 4.00 ± 0.25 cm that is significantly lower ($p < 0.05$) than the biochar and the control plants (Table 5). Complete seed germination was occurred in all pot types.

Table 5: Basil physical parameters. Mean value (Av.) of fresh weight, dry weight and height to the 3 main shoots from 5 pots of 3 different substrate types. Fresh weight of produced biomass was measured with and without roots. Roots were cut off at the starting point of the apical basil stem. Standard Deviation (SD) of mean values are reported.

***O. Basilicum* substrate**	**Fresh Weight (g)**	**Fresh Weight no roots (g)**	**Dry Weight (g)**	**Height (cm)**
SOIL Av.	1.59	1.39	0.19	6.07
SD	0.45	0.36	0.06	1.42
BIOCHAR Av.	2.45	2.12	0.24	6.07
SD	0.49	0.45	0.06	1.33
COMPOST Av.	0.90	0.76	0.10	4.00
SD	0.14	0.11	0.01	0.25

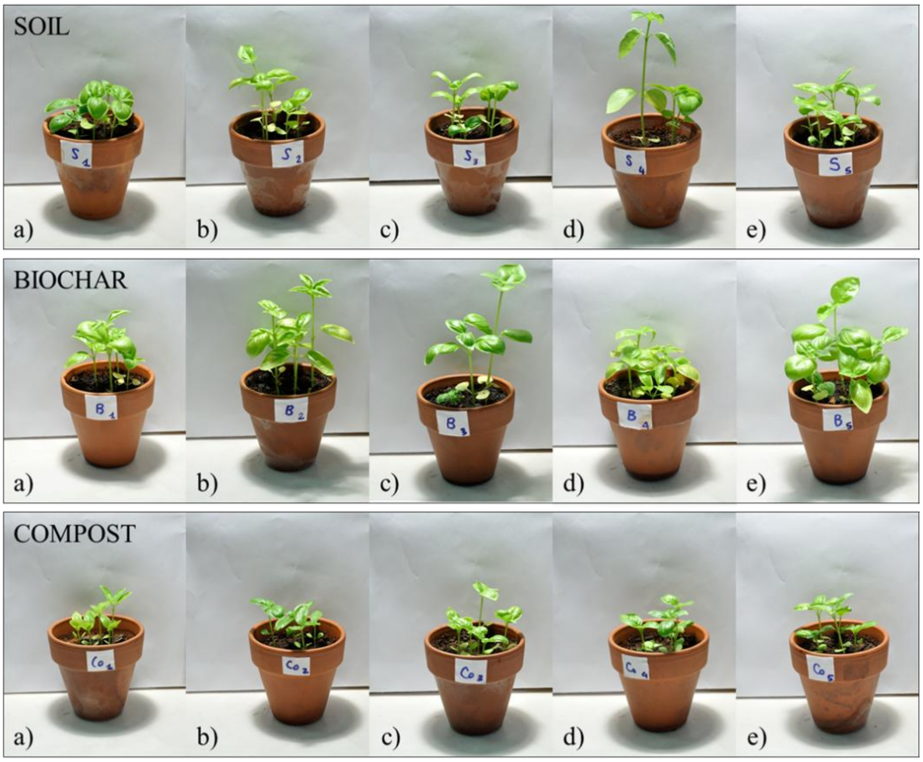

Figure 8. *Ocimum basilicum* after 55 days of experimental trial. Control substrate, soil, soil + 30% w/w biochar and soil +30% w/w compost. Five seeds for each substrate type were planted in 5 pots. The set of biochar pots shows a greater biomass growth.

Soil substrate enriched with 30% biochar showed interesting growth effects on *Ocimum basilicum* growth (Table 6). Biochar recorded significantly better behaviour as amendment for aromatic plant production compared to compost. Plants grown in 30% biochar substrate, without adding any chemical fertilizer into the test pots, exceeded the control plants. Gasification biochar introduces indeed some physical and chemical improvements to soil properties, such as carbon enrichment and nutrient availability enhancement, rising of pH value and helping soil water content [50-54]. These experimental findings lead to the estimation of the potential increase of the cultivations grown by S.A.B.A.R. using biochar as soil amendment. The mean yield of basil production inside the current greenhouse is 70 t/year [44]. Considering the enhancing effects on biomass rate brought by biochar on soil, the fresh basil production could be raised by 53%. Thereby, gasification biochar application to the S.A.B.A.R. greenhouse soil could considerably increase profit.

Table 6: Basil physical parameters. Mean value (Av.) of fresh weight, dry weight and height of the 3 main shoots from 5 pots of 3 different substrate types. Fresh weight of produced biomass was measured without roots. Roots were cut off at the starting point of the apical basil stem. Standard Deviation (SD) of mean values are reported.

O. Basilicum	**SOIL**	**BIOCHAR**	**COMPOST**
Fresh Weight (g)	1.39±0.36	2.12±0.45	0.76±0.11
Dry Weight (g)	0.19±0.06	0.24±0.06	0.10±0.01
Height (cm)	6.07±1.42	6.07±1.33	4.00±0.25

4. Conclusions

An experimental-driven modelling of green waste gasification applied to the S.A.B.A.R. landfill scenario was proven to be an efficient pathway to a better use of this biomass source.Starting from 18294 tons of green waste, it is possible to obtain approximately 18 millions of Nm^3 of syngas every year. Using this syngas as fuel in the existing CHP engines will increase the electrical landfill power production to 1.843 MW adding also 2.037 MW of thermal power. This increased energy yield will be remunerated through subsidies for renewable energy production. In such a way, considering the investment costs of the gasifier 5 M€, the payback time is assessed to be 6 years. In addition, the biochar produced can be used to improve the basil cultivation in the landfill greenhouses. Results show an increase in the basil production using soil mixed with 30% wt. of biochar compared with standard soil. This application can lead to more efficient and sustainable agricultural processes, giving new impulse to bio-energy production and recycling of by-products in a circular economy context.

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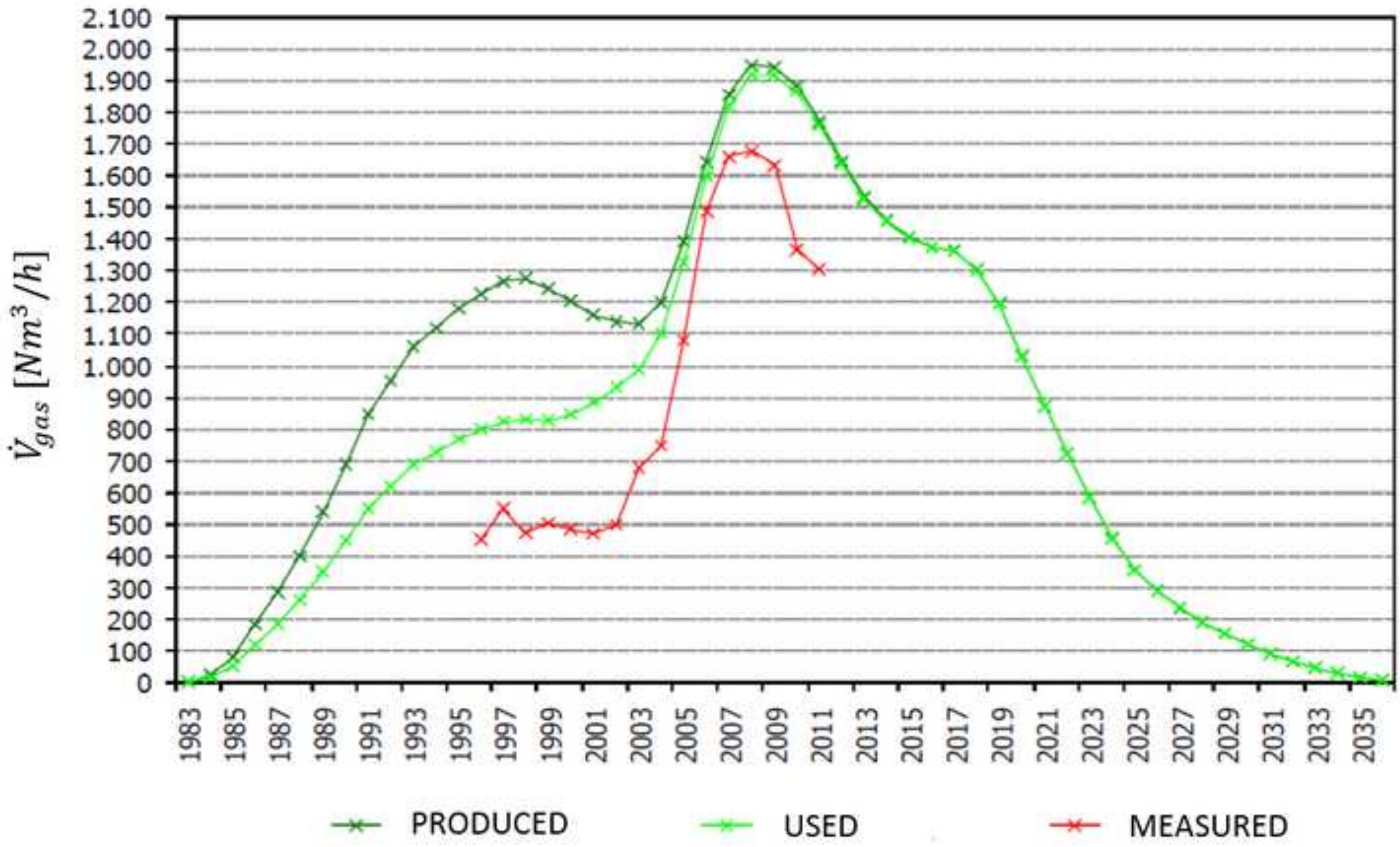

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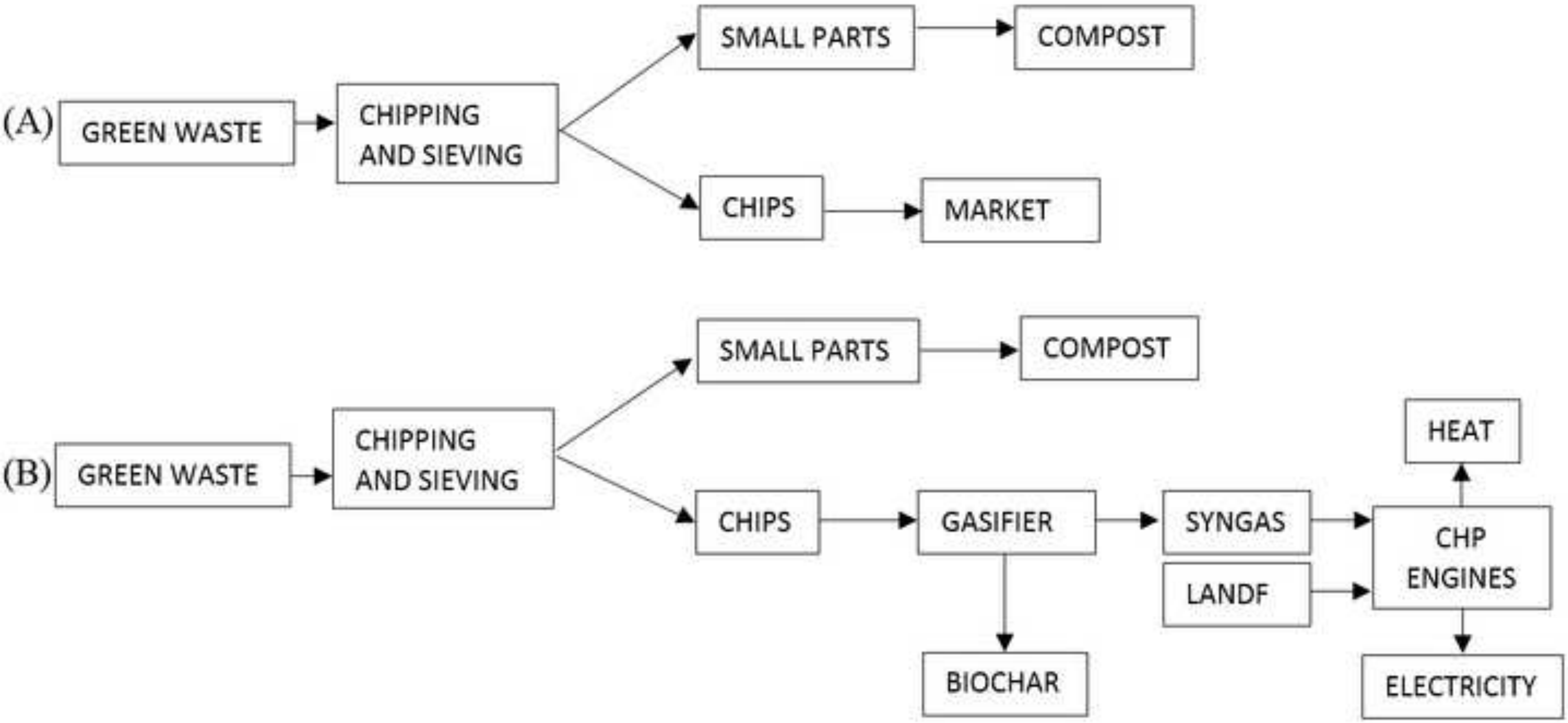

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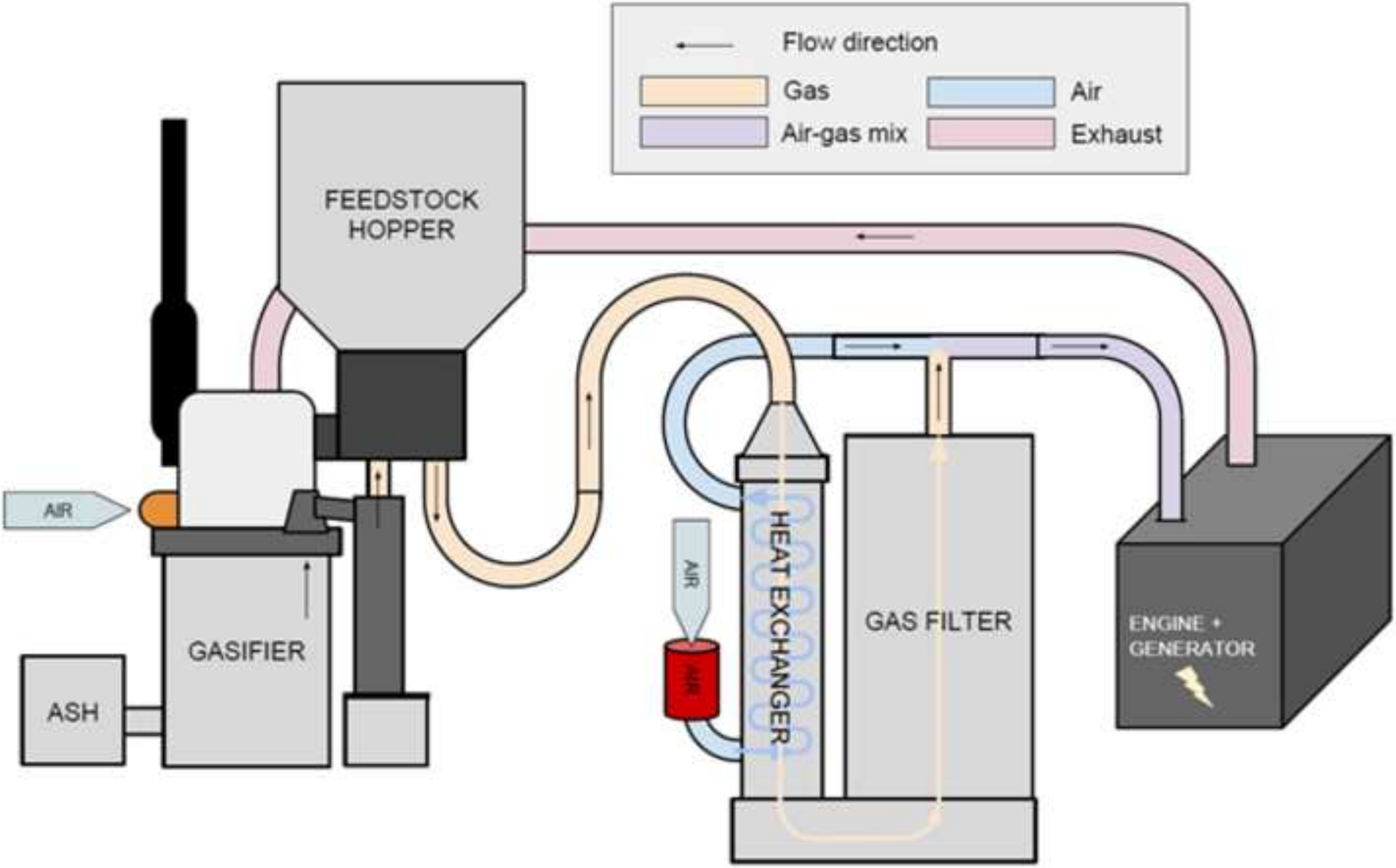

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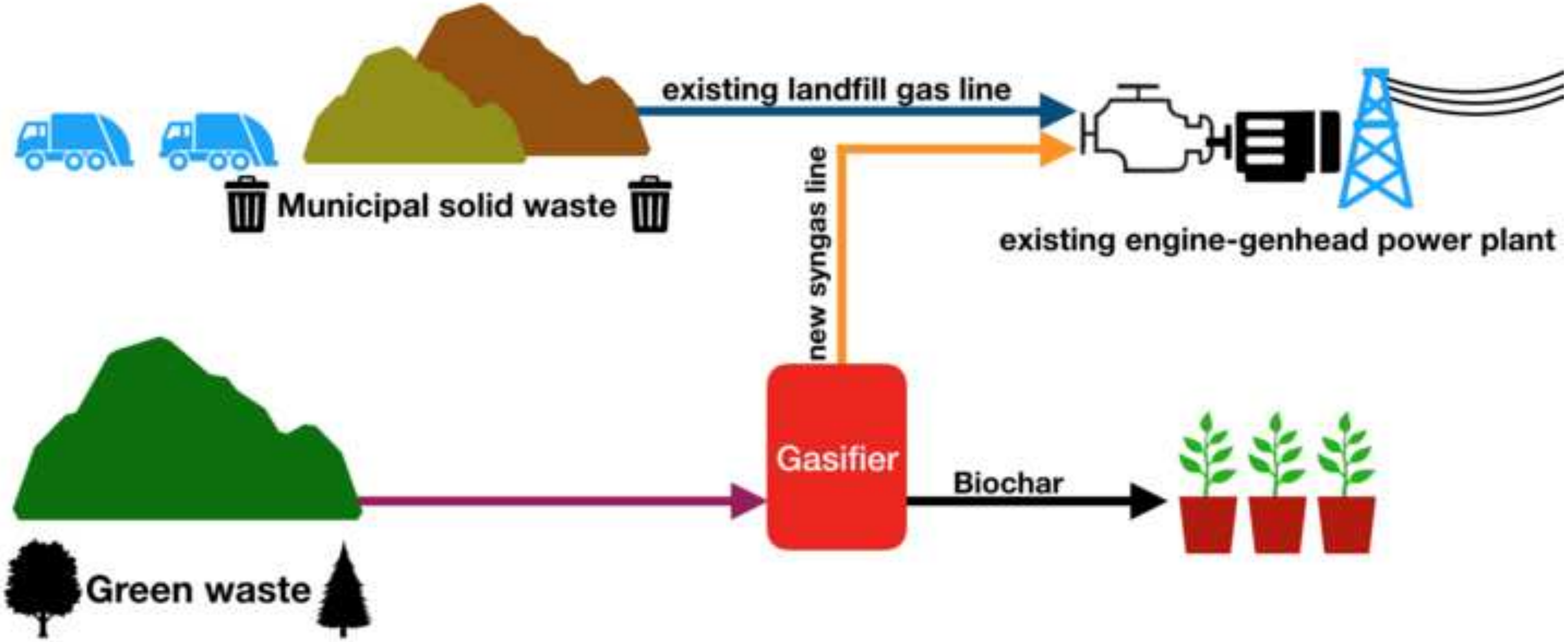

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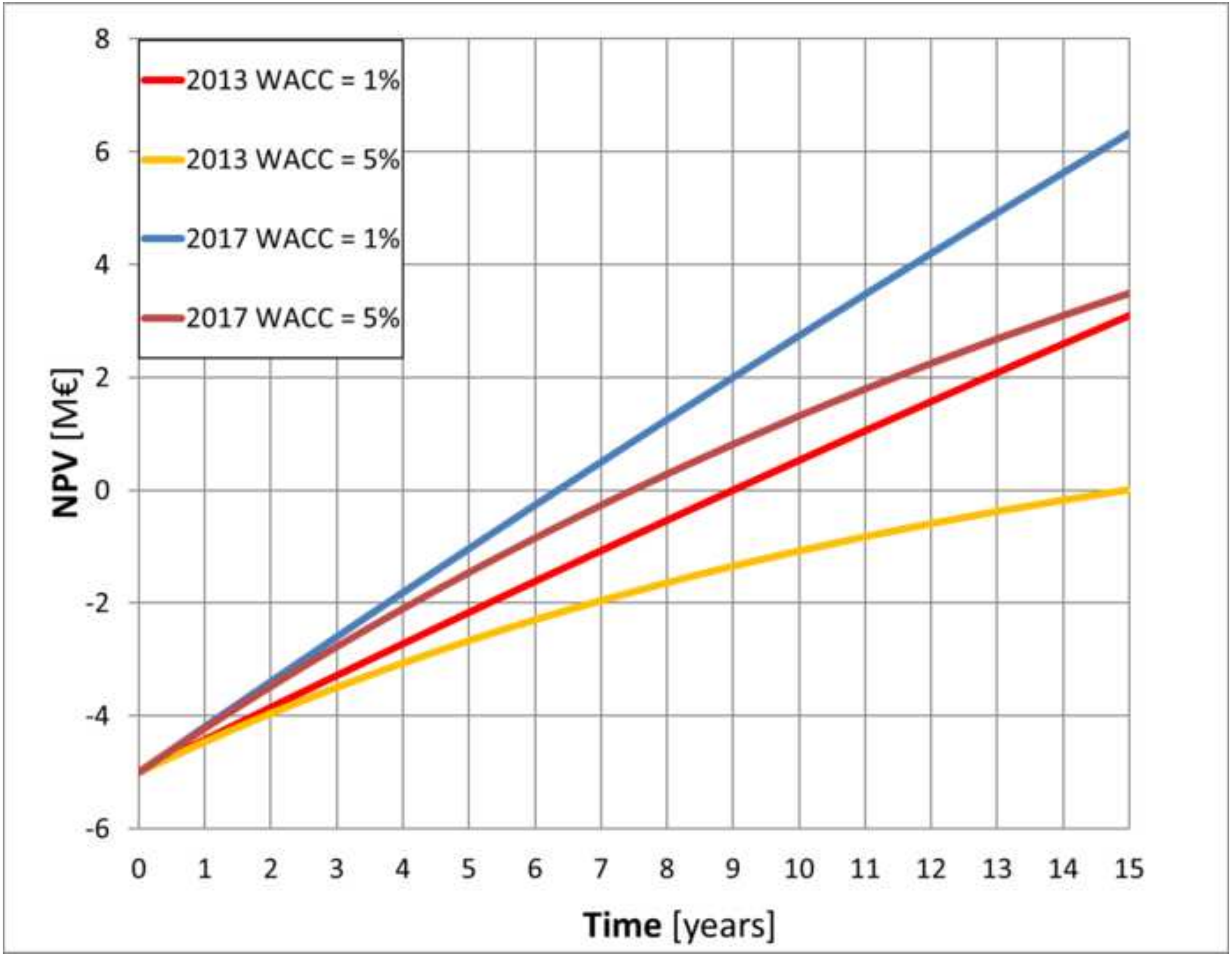

***Detailed Response to Reviewer Comments**

I am very much thankful to the reviewers for their work. I have revised my present research paper in the light of their useful suggestions and comments, the corrections in the manuscript were made in red color. I hope my revision has improved the paper to a level of their satisfaction:

Reviewer Comments:

Reviewer #1:

1. It is highly recommended to revise the language in abstract :methodology, and results)use past tense instead present tense.

We fixed this issue, now the past tense is used in the whole manuscript.

2. Keyword "CHP" avoid usage of abbreviation.

We substituted CHP with combined heat and power in the keywords.

3. Page 4 "The green waste management issue also affects highly inhabited areas, i.e. Rome produces about 15,000 tons of green waste every year [13]. Update reference and information.

Reference and information are now updated. New reference consists in the uffical periodical report of the municipality of Rome: [13] Comune di Roma. Produzione e ciclo dei rifiuti, available on: https://www.comune.roma.it/web-resources/cms/documents/Report_RIFIUTI_2015.pdf

4. Highlight the novelty at the end of introduction.

The following sentence was add at the end of the introduction part in order to underline the innovative content of the work: “In this work, gasification of green waste is validated through experimental tests in a small-gasifier equipped with an IC engine. Results from experimental tests were used to discuss the economical advantages of landfill revamping through the coupling of a gasification stage to the existing landfill gas power plant. Finally, basil growth tests were used to prove the further advantages of gasification biochar usage as soil fertilizer.”

5. Some information regarding waste handling in the site can be discussed briefly in methodology part

The following paragraph was added: “The incoming green waste is discharged on a concrete platform. Material handling grapples loads the green waste into the hopper of the chipping facility. The chipper is equipped with a sifter with 20 mm holes screen. The biomass that has a dimensions between 20 and 150 mm constitute the valuable material, while the fine particles with dimensions below 19 mm are disposed of in the composting plant.”

6. "the cost of transport of the S.A.B.A.R. wood chips ranges from 13 to 16 €/ton, this cost is three time the wood chips commercial value". Why, what is the distance and transferring cost??

As reported in the text, the wood chips are transferred to biomass combustion plants which are about 200 km from the site. According to reference [32], transporting cost range from 4 to 5 €/m^3 for a transport of 200 km. Considering a bulk density of 300 kg/m^3 for the wood chip at 40% of moisture [32], the cost of transport of the S.A.B.A.R. wood chips is calculated as follow:

(4 €/m^3)/(300 kg/m^3) = 0.0133 €/kg = 13.3 €/ton
(5 €/m^3)/(300 kg/m^3) = 0.0166 €/kg = 16.6 €/ton

therefore the total cost of the woodchips ranges from 18.3 to 21.6 €/ton. This value is nevertheless viable for the power plant owners because “high quality” dry woodchips cost up to 120 €/ton [34].

The last sentence was also added to the text.
Authors also found a typo in the previous version of the manuscript, where fuel density was reported erroneously as kg/m2.

7. is the landfill closed or still operation, provided more details about the site the total amount of waste received and the percentage of wood waste?

The landfill is still in operation, in 2017 it collected 42000 tons of not-recycled waste and about 20000 tons of green waste. These informations were added in section 2.1 according to the periodical shareholder report produced by SABAR.

8. Page 6, eq1: explain what is the LHV??

Thank you for outlining the missing explanation.
We added this sentence ”LHV_gas [MJ/Nm3] is the landfill gas lower heating value”.

9. Section 2.3 it is necessary to characterize the produced bio-char. Measurement of Surface area, porosity, FTIR are recommended.

Thank you for outlining this. The characterization of the biochar used is reported in [40]. We also reported the most relevant data in section 2.3.

10. Page 19" This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors" remove this part from conclusion

Thank you for the comment, the part was removed.

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Reviewer #2:

The study of the integration system of landfill biogas with biomass gasification is meaningful for the treatment of landfill. The present version of the manuscript is more likely a report, rather than an academic paper. The academic significance of the work should be obvious in the manuscript.

1. A proof reading by a native English speaker should be conducted to improve language quality. For example, P4/L47: "convert" should be replaced by "converting", L104: the word "range" should be replaced with "ranging" etc.

Thank you for the comment, the work was revised by a native speaker in order to improve the language level.

2. L41-42: the expression "400000 tons/year equivalent to 86 kg/year" is not very clear..

Thank you for your comment, the sentence was revised as follows:
“The amount of green waste collected in Italy every year is more than significant; a study regarding the region of Emilia Romagna estimates a production of about 400,000 tons/year, leading to a *pro capite* amount of 86 kg/year”

3. L48-50: The sentence is not clear and need to be rewritten.

The sentence was rearranged as follows:

“Thanks to a higher ideal conversion efficiency, gasification stands out against the other thermochemical technologies. Gasification consists in the thermal decomposition of the biomass into a fuel gas (syngas) through under-stoichiometric reactions”.

4. L69-70: It's said that the core idea of this work is based on waste chipping and sieving process, but in the following part no further explanation about them is given. How is the word "core" represented in the work?

The word was used improperly. The core idea is the gasification. Chipping and sieving are just two processes necessary to implement the idea within existing facilities. For these reasons the paragraph was changed as follows:

“The core idea of this work consists on the virtuous approach that can arise from the use of gasification within existing green waste management sites. The idea is based on the green waste chipping and sieving processes within existing landfill sites”.

5. L138: Authors stated that the gasification process is integrated with landfill anaerobic digestion, but there isn't any process related to landfill digestion. Relevant detailed illustration is necessary.

Thank you for the comment. First of all the native speaker we engaged for the spell check suggestd to use landfill gas instead of biogas. The text was corrected accordingly to this suggestion. Once the landfill is covered, the quality of the anaerobic digestion is derived from the maximum power production. To better explain the integration Figure 6 was added, while, in the results, the following sentence was used to better describe the effects of the gasification-landfill integration.

“The decay in the anaerobic digestion processes can be outlined by the production trend reported in Figure 2. The original power plant was capable of 4268 kW of power, according to the tech data reported in Table 1. The last landfill reading of anaerobic digestion gas production shows a maximum electrical power production of 2173 kW, less than half of the nominal power. The syngas produced through gasification can partially balance out the descending landfill gas productivity, raising the total power production from 2173 kW to 4016 kW when using landfill gas + syngas, in the same way the thermal power will rise from 2401 kW to 4438 kW”.

6. L173: it's said that the ash content of pure wood is higher, but in Table 2, things are just the opposite. Please check it carefully.

Apologies for the inconvenience, the table was ok, while the text was deceptive. The sentence was rewritten as follows:

“Ash content is higher in green waste than in pure wood due to the presence of bark in the biomass collected in the site”.

7. Please give an explanation for the equation 7.

Sorry, there was a mistake in the equation as it was presented in the text. The corrected equation (now displaying in the text) is:

η_tot= (3.6 x P_el)/(HHV_bio,dry x m_bio,dry)

Total efficiency is the ratio between electrical power produced by the IC engine generator (P_el) and the chemical power of the inlet biomass (HHV_bio,dry x m_bio,dry). The conversion parameter 3.6 is needed to obtain kW at the denominator, in fact HHV_bio,dry is 18.8 MJ/kg and m_bio,dry is 18.18 kg/h.

8. The system performance is related to many parameters, such as annual biomass availability, gasifier characteristics. The effect of the parameters on the system operation is not clear. The result is important for the application of the integration system.

Thank you for the comment. In order to give the readers a better understanding of the effects of the above-mentioned parameters 2 new paragraphs were added to the text.
In section 3.1:
“The calculation of the gasification efficiency is described in Equation 6. It is the ratio between the chemical energy in the gas and the chemical energy in the fuel biomass. Given the above-mentioned Equation 6 it is possible to deduce the effect of a different gasifier design. The scaled-up solution described in this work uses the results of the pilot-scale experimental analysis as basis. A full-scale reactor, specifically designed for green waste management, might not have the same efficiency recorded in the preliminary tests on the PP30 gasifier. An increase in the efficiency leads to a linearly increase of the power production for a fixed amount of fuel managed”.

In section 3.2 we added a comparison between two possible biomass availability scenarios:

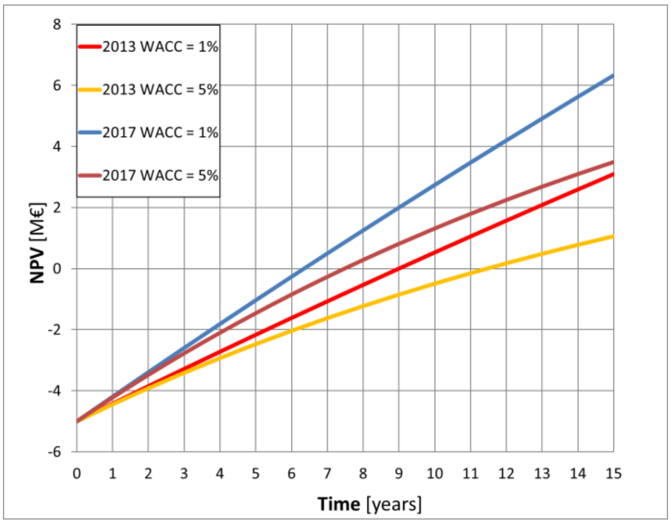
Two scenarios are here reported considering low biomass availability (2013 data) [44] and high biomass availability (2017 data) [32]. About 8113 tons of dry green-waste-derived wood chips were available in 2013 and the value peaked at 11160 tons in 2017. The gasifier was sized considering 7500 hours/year of operation and the 2017 biomass availability. A maximum gasifier thermal power input of 7.77 MW was calculated. Therefore, the syngas produced by gasification has a maximum chemical power of 4.5 MW. The decay in the anaerobic digestion processes can be outlined by the production trend reported in Figure 2. The original power plant was capable of 4268 kW of power, according to the tech data reported in Table 1. The last landfill reading of anaerobic digestion gas production shows a maximum electrical power production of 2173 kW, less than half of the nominal power. The syngas produced through gasification can partially balance out the descending landfill gas productivity, raising the total power production from 2173 kW to 4016 kW when using landfill gas + syngas, in the same way the thermal power will rise from 2401 kW to 4438 kW as derived from 2017 biomass availability.

Gasification of green waste will substitute the landfill gas flow reduction and it is also more profitable in comparison to the sale of green waste. In fact, S.A.B.A.R. benefits from the selling of the electrical energy produced through the “Certificati Verdi” feed-in-tariff mechanism [45]. The profit from 1 MWh of electricity produced from landfill gas is 79.16 €. Using the gasifier sub-system, an increase of the produced electrical energy of about 13822.5 (9862.5) MWh/y is achieved considering 2017 (2013) data. The profit is 1094189 €/year considering 2017 data and it is 780715 €/year considering 2013 data, more than ten times higher than the sale of the biomass on the market which has a profit of about 66500 €/year.

[...]

The payback time of the gasifier investment is acceptable. In fact, in the worst case the Return Of Investment (ROI) is about 11 years with WACC = 5% and minimum biomass availability (recorded in 2013), while the best case is achieved with WACC = 1% and maximum biomass availability, the respective ROI is about 6 year. A further important result of the NPV analysis is the Internal Rate of Return (IRR) defined as the value of WACC that nullify the NPV value. The IRR values range from 7.97% (worst case) to 14.9 % (best case): a reasonable range for this kind of investments [48].

[...]



Energy and biochar co-production from municipal green waste gasification: a model applied to a landfill in the north of Italy

Simone Pedrazzi*, Giulia Santunione, Andrea Minarelli, Giulio Allesina

BEELab (Bio Energy Efficiency Laboratory, Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Italy)

* Corresponding author: Simone Pedrazzi, Department of Engineering "Enzo Ferrari", Modena Italy. Mail: simone.pedrazzi@unimore.it

Abstract

This work discusses the advantages that can be obtained from the integration of landfill gas with biomass gasification. The case study presented consists of a landfill located in the province of Reggio Emilia, in the north of Italy. Landfill gas from municipal-waste fuels four internal combustion engines with overall nominal power of 2 MW, the electricity is sold back to the grid, while the thermal power is used for the heating of an industrial greenhouse compartment for basil production. Within the same facility, green waste is collected from the surrounding municipalities then chipped and sieved. Fine particles are disposed into a composting plant close by, while the sieved fraction is sold to the market for electricity production in large-scale boiler-based power plants. The idea here presented and discussed consists of the implementation of a gasifier to convert the sieved fraction of green waste into a syngas fuel directly on site. Syngas is blended with the landfill gas and then fed to the gas engines. In this work green waste gasification is tested in a commercial small-scale gasifier, proving that sifted green waste is a suitable fuel for this application. A specific consumption of 1.2 kg/kWh and a total electrical efficiency of 16.22% were measured. The sizing of the full-scale gasification facility is based on both the experimental results and data about the local availability of green waste. The economic return of the investment is then discussed. Finally, a further level of integration between gasification and the existing site is proposed: gasification-derived biochar is investigated as soil amendment for the on site company at the landfill that grows basil commercially. Results of 55 days in vivo tests show an increase in the biomass production of the basil of 53% compared to the control test group.

Keywords: landfill, green waste, gasification, combined heat and power, biochar, basil.

1. Introduction

Green waste is an unavoidable by-product produced by municipalities, it is obtained from the maintenance of public green areas, municipal parks and forestry [1]. Together with other municipal waste material, it represents one of the urgent challenges to face for increased sustainability of our societies [2, 3]. In this context, the utilization of the green waste for bio-energy production is a promising solution [4, 5]. Green waste consists of: dead trees and stomps, pruning of trees and shrubs, leaves, grass clippings and dirt [6, 7]. Due to its low energy density and its high moisture content, it is usually collected and sent to composting plants, landfill etc. [8]. In all the cases above, the disposal of green waste represents expenditure for the municipality. Furthermore the composting process, a competitor technology to the energy conversion, releases Volatile Organic Compound (VOC), methane and carbon dioxide that contributes to the atmospheric pollution and climate change [7-11]. The amount of green waste collected in Italy every year is more than significant; a study regarding the region of Emilia Romagna estimates a production of about 400,000 tons/year, leading to a *pro capite* amount of 86 kg/year [12]. The green waste management issue also affects highly inhabited areas, i.e. Rome produces about 82,000 tons of green waste every year [13]. Citing the World Energy Council 2016: “the waste management sector faces a problem that it cannot solve on its own. The energy sector, however, is considered to be a perfect match, because of its need to continuously meet a growing energy demand.” [14].

The market offers several technologies capable of converting organic biomass into energy efficiently. Thanks to higher ideal conversion efficiency, gasification stands out against the other thermochemical technologies. Gasification consists in the thermal decomposition of the biomass into a fuel gas (syngas) through under-stoichiometric reactions [15, 16]. As common practice, the gas is cleaned from pollutants (particulates, tars, soot) and then burned into internal combustion engines for combined heat and power production [17, 18]. Gasification of ligno-cellulosic biomasses produces sustainable energy as well as a valuable by-product known as biochar with good soil amendment properties [19-23]. Biochar is defined as a carbon-rich product produced through thermal degradation [24, 25]. Because of its high porosity, biochar can hold water and release it to the plant during periods of water scarcity [26, 27]. Therefore, the production of biochar, in combination with its storage in soil, has been suggested as a promising way to capture and store atmospheric CO_2 [28,29].

Even though biomass gasification is an efficient technology, it has some disadvantages such as restricted fuel flexibility and high cost. These issues become more significant in large industrial applications. An accurate gasifier design and complex control strategies can nullify the risk of power plant shutdowns and decrease the Operation Expenditures (OPEX).

This work focuses on the analysis of a virtuous solution for green waste energy conversion in existing waste management sites. The proposed system integrates the existing facilities refining the economical sustainability with the further benefit of biochar production for soil improvement. Currently, the best practice for green waste management consists of its collection and chipping in order to reduce its volume. The resulting biomass is sieved using different methods. The fine fraction has a high content of dust, rock and bark and it is disposed of in landfills or in composting plants. The sifting process selects biomass with a high enough quality to be sold to the market as fuel for Combined Heat and Power (CHP) combustion power plants. The core idea of this work consists on the virtuous approach that can arise from the use of gasification within existing green waste management sites. The idea is based on the green waste chipping and sieving processes within existing landfill sites. The sieved biomass with low quality is disposed of in compost plants and the remaining biomass is used as fuel in a gasifier reactor to make biochar and syngas. Syngas is filtered and mixed with the landfill gas; the gas mixture is used as fuel in the existing CHP engines of the landfill power plant. In this way, CHP gas engines will produce more power compared with the conventional scenario, furthermore syngas will compensate for the decrease of the methane content of landfill gas throughout the years [30, 31]. This advantage increases the economical profitability of the landfill.

Without a proper distributed heating network, the heat produced by the CHP modules in landfills is hard to exploit in a proper way, especially because landfill sites are usually built far from those urbanized areas that can benefit from the heat production. In this paper, the gasification of sieved green waste is modelled and applied to a case study where the heat released by the engines is used in an efficient way. The company that manages the landfill is named “S.A.B.A.R.” and it is located in the north of Italy close to the city of Novellara, in the province of Reggio nell’Emilia. Here, four IC engines use landfill gas to produce about 2 MW of electrical power and 2.5 MW of thermal power. A substantial fraction of this thermal power, about 1.8 MW, is used to heat 2 greenhouses with a total surface area of about 4,500 m^2. Basil is cultivated in the greenhouses. Currently, the company manages public and private green waste collected from the surrounding municipalities. After chipping and sieving it, the fine part of the green waste is exploited in a composting plant close to S.A.B.A.R. and the remaining part is sold on the market for about 5 €/ton.

In this work, gasification of green waste is validated through experimental tests in a small-gasifier equipped with an IC engine. Results from experimental tests were used to discuss the economical advantages of landfill revamping through the coupling of a gasification stage to the existing landfill gas power plant. Finally, basil growth tests were used to prove the further advantages of gasification biochar usage as soil fertilizer.

2. Material and methods

2.1 Landfill description

S.A.B.A.R. is a multi-utility company owned by several municipalities in the province of Reggio nell'Emilia, in the north of Italy. Since 1983, S.A.B.A.R. operates the landfill depicted in Figure 1. Three photovoltaic power plants are placed on the closed landfill digs for a total installed peak power of 2.15 MW. In 2017, S.A.B.A.R. collected about 42000 tons of non-recycled waste coming from the municipalities in the immediate vicinity. In addition, 37989 tons of green waste was processed in the same year [32]. The green waste collected is composed of 32% wt. grass clipping and leaves, and 68 % wt. wood prunings and wood logs. The incoming green waste is discharged on a concrete platform. Material handling grapples load the green waste into the hopper of the chipping facility. The chipper is equipped with a sifter with 20 mm hole screen. The biomass that has a dimensions between 20 and 150 mm constitute the valuable material, while the fine particles with dimensions below 19 mm are disposed of in the composting plant. In 2017, about 18294 tons of wood chips with a moisture content of 39% were available on a yearly basis [32]. Currently, this biomass is sold to companies that operate biomass combustion power plants, which are, on average, 200 km from S.A.B.A.R. The cost and the environmental impact of the transport is massive. A study regarding the transport of forest chips and forest industry by-products with large truck-trailers in Finland reports a transporting cost that ranges from 4 to 5 €/m^3 for a transport of 200 km [33]. Considering a bulk density of 300 kg/m^3 for the wood chips at 40% of moisture [33], the cost of transport of the S.A.B.A.R. wood chips ranges from 13.3 to 16.6 €/ton. Therefore, the total cost of the woodchips ranges from 18.3 to 21.6 €/ton considering the raw biomass cost of 5 €/ton. This value is nevertheless viable for the power plant owners because "high quality" dry woodchips cost up to 120 €/ton [34].

Figure 1: S.A.B.A.R. landfill

The technical specs of the engines are reported in Table 1. The landfill gas data reported here are the average values that refer to 2015. The total electrical and thermal power output is calculated as follows:

$$P_{el} = \dot{V}_{gas} LHV_{gas} \eta_{el} \tag{1}$$

$$P_{th} = \dot{V}_{gas} LHV_{gas} \eta_{th} \tag{2}$$

Where P_{el} [kW] is the electrical output, $\dot{V}_{gas}$ [Nm^3/h] is the landfill average gas production, η_{el} [%] is the electrical efficiency of the unit, LHV_{gas} [MJ/Nm^3] is the landfill gas lower heating value and η_{th} [%] is the thermal efficiency of the unit. The engine's cooling circuit is connected to a heat exchanger that is connected to a district heating line and to the heating circuit of the greenhouses. Not the entire thermal output of the engine is used to heat the greenhouses, in fact part of it is used in a district heating line serving the landfill facilities. During the cold season, the maximum heating load of the greenhouses, in order to have a constant internal temperature of 30 °C is about 1.8 MW and it is calculated as follows:

$$\dot{Q}_{gh} = \dot{m}_{H_20} c_{p,H_20} (T_{in} - T_{out}) \tag{3}$$

where $\dot{Q}_{gh}$ [kW] is the maximum heating load of the greenhouses, $\dot{m}_{H_20}$ [kg/h] is the water mass flow of the heating circuit of the greenhouses (77500 kg/h), c_{p,H_20} [J/(kg K)] is the water specific heat (4.186 J/(kg K)), T_{in} [°C] is the temperature of water at the inlet of the heating circuit of the greenhouses and T_{out} [°C] is the temperature of water at the outlet of the heating circuit of the greenhouses. The landfill gas production decreases every year because today the landfill is full and the existing waste fermentation has a downward trend. Figure 2 reports the calculated flow of produced and usable landfill gas from 1983 to 2035 and the measured flow from 1996 to 2013 [36]. The measured flow is lower in respect of the calculated flow, this phenomenon was probably due to the introduction of waste sorting in the waste disposal process. In fact, with this method, the amount of organic waste to the landfill is negligible and consequentially the landfill gas production is low. Therefore, the model estimates that the landfill gas production will end in 2035 and, looking at the measured production, this deadline will happen earlier. For this reason, the substitution of landfill gas with another gaseous fuel is mandatory to assure the operability of the CHP engines and greenhouses. Syngas from green waste gasification or biogas from digestion of anaerobic organic waste can be two valuable alternative fuels. This paper introduces green waste gasification coupled with landfill anaerobic digestion. Figure 3 compares the status quo (A) and a new scenario with a gasification stage (B). Here the syngas produced from green waste is used as fuel in CHP engines together with landfill gas.

Table 1: CHP engines and landfill gas characteristics

Engine type	GE Jenbacher JGS 320 [35]
Max. electrical output [kW]	1067
Max. power input [kW]	2608
Thermal efficiency [%]	45.2
Electrical efficiency [%]	40.9
Total efficiency [%]	86.1
Landfill gas methane content [% vol.]	47.6
Landfill gas production [Nm^3/h]	1200
Landfill gas lower heating value [kWh/Nm^3]	4.43
Landfill gas power input [kW]	5316
Total electrical output [kW]	2173
Total thermal output [kW]	2401

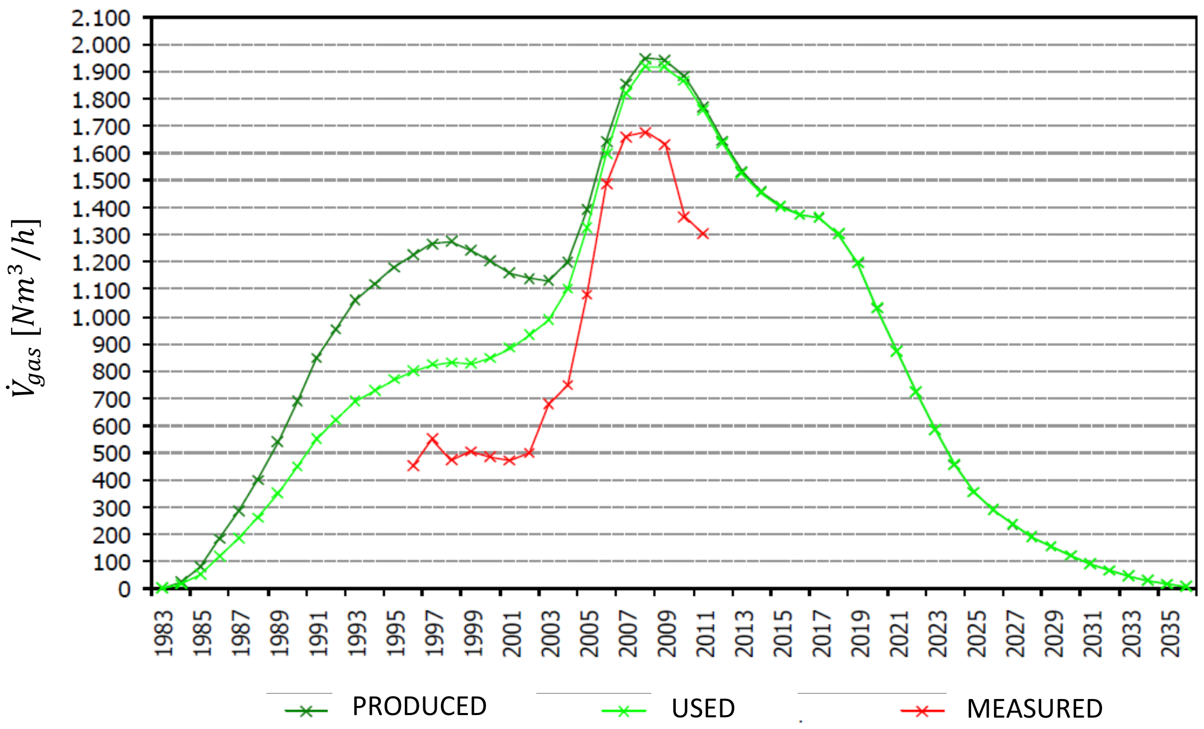


Figure 2: Modelled landfill gas production and comparison with measured data [36]

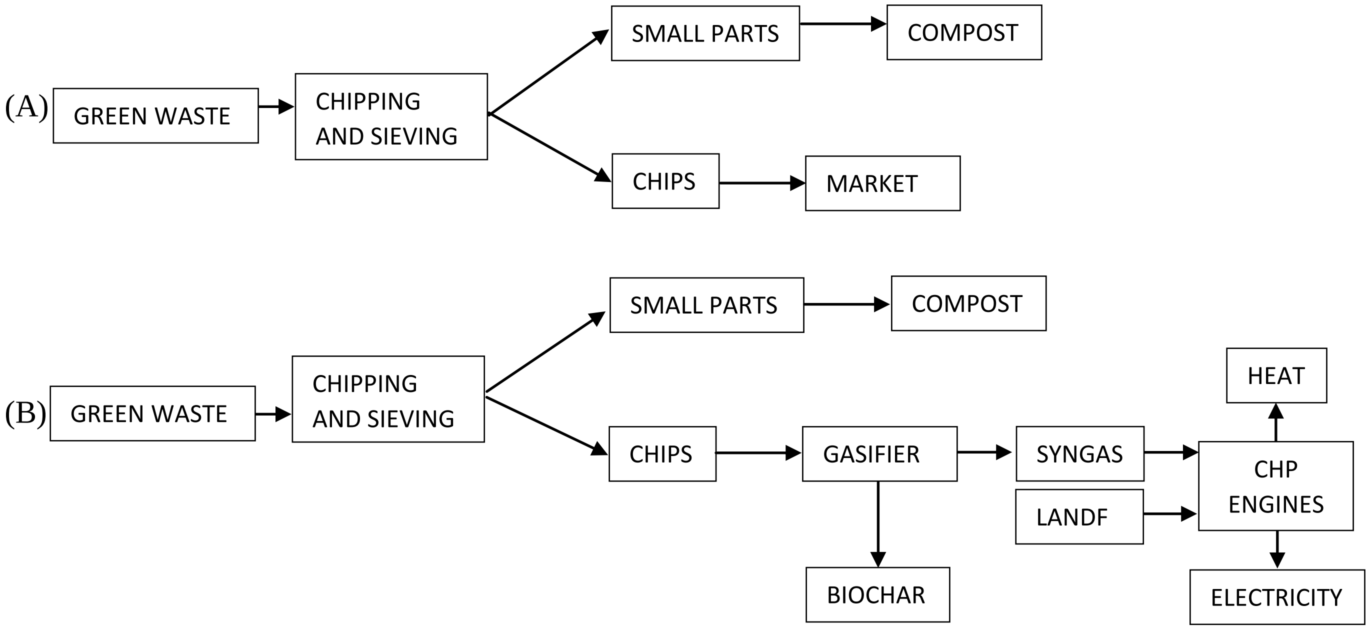


Figure 3: (A) S.A.B.A.R. actual operation of green waste; (B) S.A.B.A.R. alternative operation of green waste

2.2 Municipal green waste gasification

In order to properly assess the feasibility of green waste conversion into commercial gasifiers, 250 kg of chipped green waste with a moisture content of 40% was sieved and dried in an industrial dryer. Figure 4 reports the green waste before and after these processes. Approximately 100 kg of dry wood chips was collected. Concerning wood chips particle size after sieving, the equivalent wood chips class is P45A according with the standard UNI EN ISO 14961-1. Ash content of the biomass was evaluated burning a biomass sample on a furnace at 550 °C for 4 hours as suggested by the ASTM E1755 standard. Biomass moisture content was calculated according to UNI EN ISO 18134-1. In addition, an elemental analysis was performed using a FLASH 2000 Organic Elemental CHNS Analyzer [37]. Table 2 summarizes results of these analyses. The higher heating value of the dry biomass $HHV_{bio,dry}$ [MJ/kg] is calculated through the Channiwala and Parikh correlation [38]:

$$HHV_{bio,dry} = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1ASH \tag{4}$$

where C [%wt.] is the biomass carbon content, H [%wt.] is the biomass hydrogen content, S [%wt.] is the biomass sulphur content, N [%wt.] is the biomass nitrogen content, O [%wt.] is the biomass oxygen content and ASH [%wt.] is the biomass ash content. These data is collected from the analysis of biomass sample that is completely dry. The composition of the collected green waste is similar to the composition of wood chips from urban prunings reported in the ECN Phyllis biomass and waste database [39]. Ash content is higher in green waste than in pure wood due to the presence of bark in the biomass collected in the site. The higher heating value of green waste is slightly lower than the higher heating value of pure wood, however it is still high enough to test this biomass in the gasification regime.

Table 2: Green waste characterization in dry conditions

Biomass composition in dry conditions			
	Case study green waste	Phyllis green waste [39] item #3342	Phyllis pure fir wood [39] item #239
Carbon content C [% wt.]	46.93	47.5	50.36
Hydrogen content H [% wt.]	5.85	5.74	5.92
Sulphur content S [% wt.]	0	0	0
Nitrogen content N [% wt.]	0.94	0.22	0.05
Oxygen content O [% wt.]	41.38	41.57	43.39
Ash [% wt.]	4.9	4.97	0.28
Moisture after drying M [% wt.]	11.1	11.08	/
Higher Heating Value in dry conditions [MJ/kg]	18.8	19.68	19.78

Figure 4: Green waste sample before and after the sieving and drying processes

To perform the green waste gasification test, a pilot scale, All Power Labs PP30 fixed bed gasifier [40] was used. The schematic of the system is depicted in Figure 5. This particular gasifier can be fed with agricultural and forestry waste biomasses with a moisture content up to 30%. It consists of two main different parts: a gas making sub-system and a power generation unit. The gas making sub-system consists of a hopper with a volume of approximately 0.3 m^3, a downdraft single-throat reactor and a drum filter. The biomass is manually loaded into the hopper and conveyed into the reactor by an auger. A sensor on the top of the reactor controls the auger feed rate. The syngas that is produced leaves the reactor and runs into a heat exchanger that transfers heat to the combustion air of the engine. The syngas produced contains two main species of pollutants: particulate matter and tar. A cyclone placed downstream from the reactor collects most of the particulate while the drum filter removes the remaining dust and tar. Once filtered, the gas flows into the Ashok Leyland 4.0-liter spark ignition engine, which is connected to a Marathon 284CSL1542 generator [40]. The power generation system is capable of a maximum of 22 kW of electrical power at 50 Hz. However, during the gasification test, the power output was kept at about 15 kW. This value was chosen far enough from the maximum power output in order to guarantee sufficient stability of the engine operation, also during feedstock refuelling. The dry biomass consumption $\dot{m}_{bio,dry}$ [kg/h] and the total electrical energy produced E_{el} [kWh] are measured in order to calculate the specific biomass consumption $s_{bio,tot}$ expressed in kg/kWh. Since the gasifier is not provided with a level sensor in the hopper, the biomass consumption was calculated by measuring its level at the beginning of the test and weighing the biomass needed to reach the same level at the end of the test. The volumetric flow rate of the syngas $\dot{V}_{syngas}$ [Nm^3/h] was indirectly calculated according to Equation 5 by measuring the gasification airflow entering the reactor through an anemometer. The N_2 content of the syngas as well as its total composition were measured with a Pollution Micro GCX gas chromatograph [41]. All the samples were drawn after the syngas filtration stage. The gasification and total efficiency were calculated according to Equations 6 and 7.

$$\dot{V}_{syngas} = \dot{V}_{air} \cdot \frac{0.781}{N_2} \tag{5}$$

$$\eta_{\mathrm{gas}} = \frac{\dot{V}_{\mathrm{syngas}} \cdot HHV_{\mathrm{syngas}}}{\dot{m}_{\mathrm{bio,dry}} \cdot HHV_{\mathrm{bio,dry}}} \tag{6}$$

$$\eta_{\mathrm{tot}} = \frac{3.6\, P_{\mathrm{el}}}{HHV_{\mathrm{bio,dry}}\, \dot{m}_{\mathrm{bio,dry}}} \tag{7}$$

Finally, the higher heating value of the syngas HHV_{gas} [MJ/Nm^3] was calculated with the following equation:

$$HHV_{syngas} = \frac{12.75H_2 + 12.63CO + 39.72CH_4}{100} \tag{8}$$

where H_2 [% vol.] is the hydrogen volumetric fraction of the syngas fuel, CO[% vol.] is carbon monoxide volumetric fraction of the syngas fuel and CH_4 [% vol.] is the methane volumetric fraction of the syngas fuel.

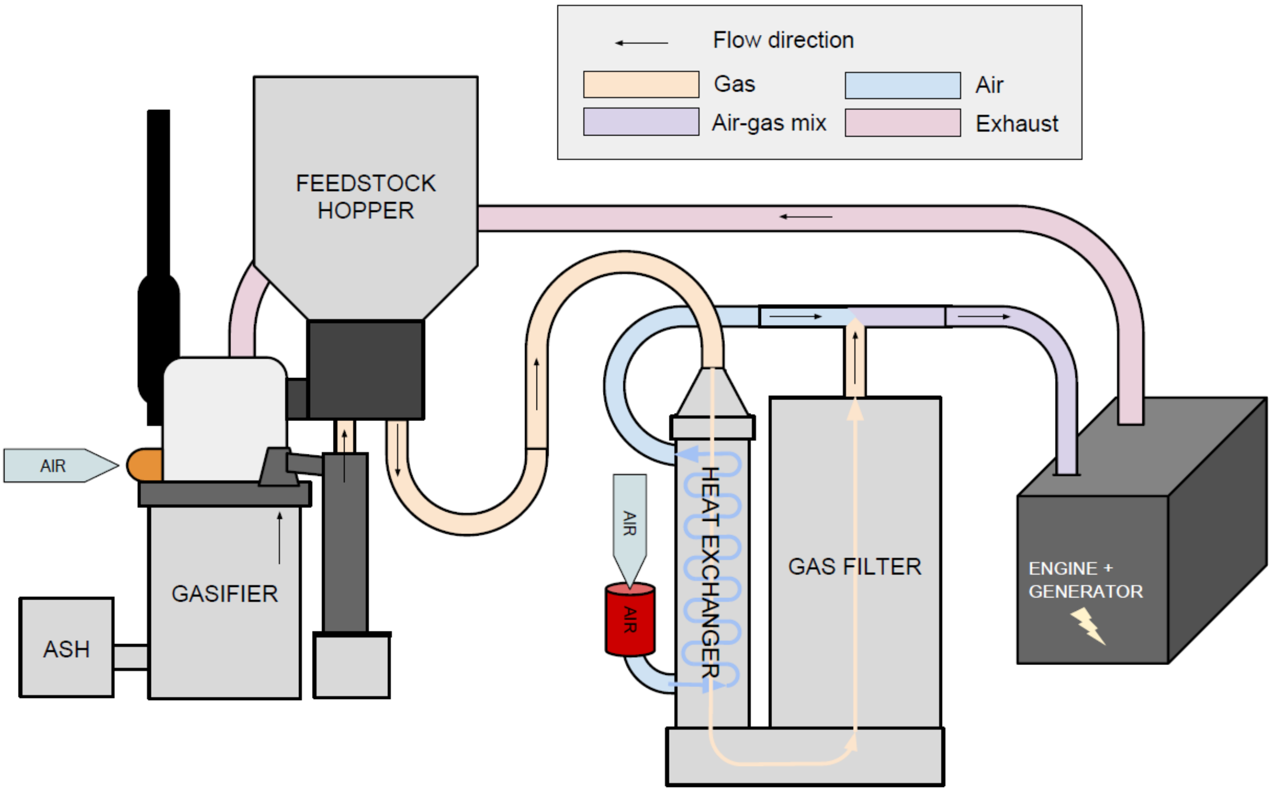


Figure 5: Schematic of the All Power Labs PP30 gasifier system [33].

2.3 Plants growth test with biochar

Beyond heating and power, the small scale All Power Labs PP30 gasifier produces a valuable by-product from green waste, represented by biochar. Its characterization is reported in a previous work [42]. Biochar BET surface is 394.4 m^2/g, real density is 2.1254 g/cm^3 and the XRF analysis indicates the presence of K, Ca, Fe and Sr in the char. In this work, an *in-vivo* experimental study was set up to investigate the effects of biochar on soil application compared to the effects of normal soil and from the organic matter of urban waste used, compost. The growth rate of the plant species *Ocimum basilicum* related to three different substrates type were considered: standard soil, soil mixed with 30% wt. of compost from organic fraction of municipal waste, soil mixed with 30% wt. of woodchip biochar. Initially, 5 seeds were planted in each terracotta. 5 pots for each substrate type were filled and put in a greenhouse equipped with red and blue LED lights. The Photosynthetically Active Radiation (PAR) was measured with a PAR sensor, model HY-MD-D 169-S. In the greenhouse, the average PAR measured was 200 ± 20 $\mu E/m^2/s$ and it was lit 12 hours per day in the germination period of the shoots (4 weeks), afterwards the light period was extended to 14 hours per day. The study was carried out indoors from February to April at the Department of Engineering “Enzo Ferrari” in Modena, Italy. The experiment lasted 55 days. The relative humidity (RH) and temperature (T) of the greenhouse were maintained automatically at 30-70% and 18-27°C by an *Arduino-based* circuit.

2.4 Characterization of plants

The *O. basilicum* culture was used to evaluate the differences among substrates types and their influence on biomass production. The germination rate in each pot was checked and the growth velocity of the plants was recorded with a Nikon D5000 camera. The height of each seedling was measured with calipers. The produced biomass weight was measured using a Radwag PS360/C/2 scientific grade scale; the precision of the instrument is 0.001 g. The results include the data from 5 repeated test for each substrate type and were processed with statistical tools: the mode, average, standard deviation and analysis of variance (ANOVA) were calculated to obtain representative and comparable indicators among the different groups of pots.

3. Results and discussion

3.1 Green waste gasification

The gasification test of the treated green waste lasted about 4 hours. After half an hour of start-up with fir wood chips, 100 kg of sieved and dried green waste was loaded into the hopper. The electrical power production was set up at 15 kW to have a significant test duration and run stability. The electrical power was dissipated through a load-bank, the thermal power (about 20 kW) was used in a dryer to reduce the moisture of the fir wood chips. After about 1 hour of gasification with green waste only, two syngas samples were analysed in a gas chromatographer in order to evaluate the gasification behaviour. Results of gas chromatography and of the gasification tests are reported in Table 3. The gas chromatography analysis was done on two dried syngas samples because the water in the gas can damage the gas chromatography apparatus. The water was removed cooling the syngas to ambient temperature and using an adsorbent medium (silica gel). Water in the gas influences the engine performance, however in the Power Pallet water condensation in the gas line was prevented by setting up the temperature of the gas to about 60 °C, for this reason the evaluation of the syngas water content is not necessary. Results showed a minimum variability of the gas components and the average higher heating value of the gas was 6.55 MJ/Nm^3. This value is in line with syngas heating value of downdraft fixed bed reactors [43]. It is therefore possible to affirm that the gasification of green waste was successful in the All Power Labs gasifier. In addition, the biomass specific consumption was about 1.2 kg of dry green waste per kWh of electricity produced, this value is a little higher than the biomass consumption given by the manufacturer (1 kg/kWh). This is probably due to the high ash content of the biomass. The calculation of the gasification efficiency is described in Equation 6. It is the ratio between the chemical energy in the gas and the chemical energy in the fuel biomass. Given the above-mentioned Equation 6 it is possible to deduce the effect of a different gasifier design. The scaled-up solution described in this work uses the results of the pilot-scale experimental analysis as basis. A full-scale reactor, specifically designed for green waste management, might not have the same efficiency recorded in the preliminary tests on the PP30 gasifier. An increase in the efficiency leads to a linearly increase of the power production for a fixed amount of fuel managed. Table 3 also reports the specific syngas production s_{syngas} [Nm^3/kg] calculated dividing the syngas flow rate by the dry biomass consumption. This data is useful to estimate the volume of syngas obtainable from a given amount of biomass.

Table 3: Dry syngas composition and gasification test results

Syngas component	Sample 1	Sample 2	Average
Hydrogen H_2 [% vol.]	18.7	18.0	18.35
Nitrogen N_2 [% vol.]	40.0	40.6	40.3
Carbon monoxide CO [% vol.]	25.3	26.1	25.7
Carbon dioxide CO_2 [% vol.]	10.3	9.4	9.85
Methane CH_4 [% vol.]	2.5	2.3	2.4
HHV_{syngas} [MJ/Nm^3]	6.6	6.5	6.55
Air flow rate $\dot{V}_{air}$ [Nm^3/h]	15.31	15.30	15.305
Syngas flow rate $\dot{V}_{syngas}$ [Nm^3/h]	29.91	29.45	29.68
Dry biomass consumption $\dot{m}_{\mathrm{bio,dry}}$ [kg/h]	-	-	18.18
Equivalence ratio ER	0.1928	0. 1927	0.19275
Specific syngas production s_{syngas} [Nm^3/kg]	1.645	1.620	1.632
Gasifier average hearth temperature [K]	-	-	900
Gasifier average reduction temperature [K]	-	-	1200
Gasification cold efficiency η_{gas} [%]	-	-	57.95
Electrical power production P_{el} [kW]	-	-	15
Total electrical efficiency η_{tot} [%]	-	-	16.22
Biomass specific consumption $s_{bio,tot}$ [$kg_{\mathrm{bio,dry}}$/kWh]	-	-	1.2

3.2. Green waste gasification applied to the S.A.B.A.R. landfill

The pilot test demonstrates that a fraction of the managed green waste can be successfully used as fuel in gasification after a proper pre-treatment. Results of the scaled tests are the basis for sizing the full-scale idea depicted in Figure 6.

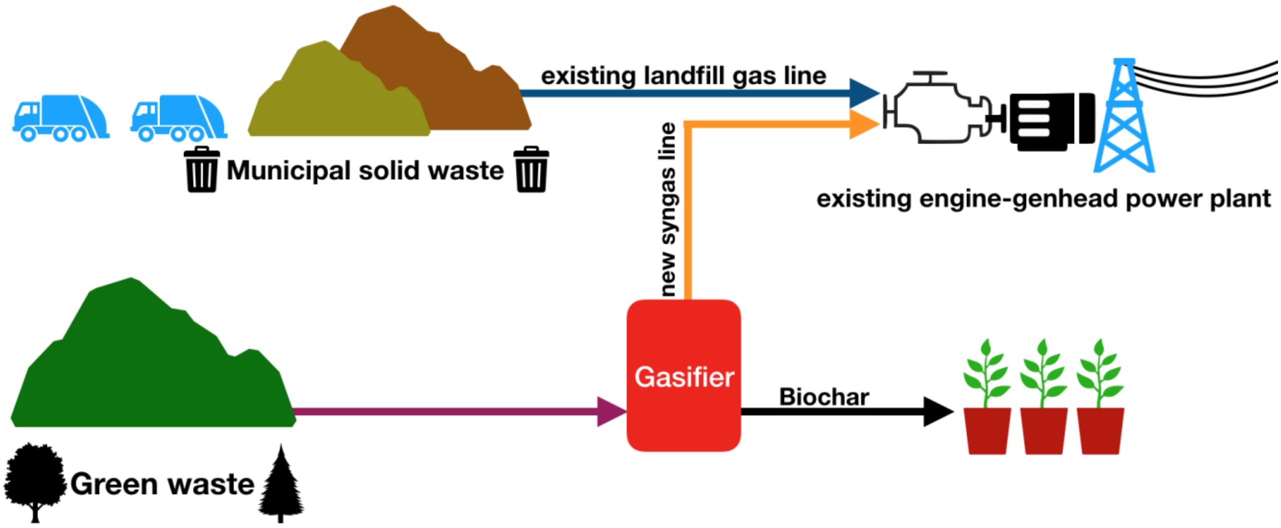


Figure 6: Landfill gas power plant coupled with green waste gasification system

Starting from the expected biomass amount, a suitable gasifier needs to be sized. The main results regarding biomass availability, gasifier characteristic and integration with CHP engines are reported in Table 4. Two scenarios are here reported considering low biomass availability (2013 data) [44] and high biomass availability (2017 data) [32]. About 8113 tons of dry green-waste-derived wood chips were available in 2013 and the value peaked at 11160 tons in 2017. The gasifier was sized considering 7500 hours/year of operation and the 2017 biomass availability. A maximum gasifier thermal power input of 7.77 MW was calculated. Therefore, the syngas produced by gasification has a maximum chemical power of 4.5 MW. The decay in the anaerobic digestion processes can be outlined by the production trend reported in Figure 2. The original power plant was capable of 4268 kW of power, according to the tech data reported in Table 1. The last landfill reading of anaerobic digestion gas production shows a maximum electrical power production of 2173 kW, less than half of the nominal power. The syngas produced through gasification can partially balance out the descending landfill gas productivity, raising the total power production from 2173 kW to 4016 kW when using landfill gas + syngas, in the same way the thermal power will rise from 2401 kW to 4438 kW as derived from 2017 biomass availability.

Gasification of green waste will substitute the landfill gas flow reduction and it is also more profitable in comparison to the sale of green waste. In fact, S.A.B.A.R. benefits from the selling of the electrical energy produced through the “Certificati Verdi” feed-in-tariff mechanism [45]. The profit from 1 MWh of electricity produced from landfill gas is 79.16 €. Using the gasifier sub-system, an increase of the produced electrical energy of about 13822.5 (9862.5) MWh/y is achieved considering 2017 (2013) data. The profit is 1094189 €/year considering 2017 data and it is 780715 €/year considering 2013 data, more than ten times higher than the sale of the biomass on the market which has a profit of about 66500 €/year. However, the investment and O&M costs of the gasifier need to be taken into account. Capital Expenditures (CAPEX) of a full scale gasifier system is about 4000 € for every kW of nominal electrical power [46], therefore a power plant sized for maximum the biomass availability has a 1843 MW (Table 3) of nominal electrical power would have a cost of 7.37 M€. However, it is fundamental to underline that, due to the uniqueness of the S.A.B.A.R scenario no engines are needed for the gasifier because the same existing engines fuelled by landfill gas will be exploited. From this consideration, a cost of the gasifier system of 5 M€ is taken into account. O&M cost of standard gasifiers is about 0.02 €/kWh [46], in this case an annual O&M cost of about 276450 €/year is considered in the scenario with 2017 data, the value decreases to 197205 €/year considering 2013 data. With these assumptions, an economical Net Present Value (NPV) analysis was performed [45]. The following formula was used to calculate the NPV value at the n-th year as the sum of the discounted cash inflow in the year from 0 to N:

$$NPV = \sum_{n=0}^{N} \frac{(I_{cv} - I_{O\&M})}{(1 + WACC)^n} - I_o \tag{9}$$

where $WACC$ is the Weighted Average Cost of Capital [47]; I_{cv} [€] is the value of the annual subsidy for the electricity produced through renewable sources; $I_{O\&M}$ [€] is the annual O&M cost of the gasifier and I_o [€] is the initial investment. Figure 7 shows the NPV analysis of the investment considering 2013 and 2017 data, N = 15 years and the WACC equal to 1% and 5%. The choice of N derives from “Certificati Verdi” subsidies regulation, WACC limits are suggested by literature [45]. The payback time of the gasifier investment is acceptable. In fact, in the worst case the Return Of Investment (ROI) is about 11 years with WACC = 5% and minimum biomass availability (recorded in 2013), while the best case is achieved with WACC = 1% and maximum biomass availability, the respective ROI is about 6 year. A further important result of the NPV analysis is the Internal Rate of Return (IRR) defined as the value of WACC that nullify the NPV value. The IRR values range from 7.97% (worst case) to 14.9 % (best case): a reasonable range for this kind of investments [48]. In addition, the system provides at least 160 tons of biochar every year. Part of it can be used as soil enhancer for the basil greenhouse cultivations, the remaining part can be sold to the market as biochar with a profit of about 1-2 €/kg [49]. Selling of biochar is not considered in the financial analysis because the effective production depends on the full scale gasification technology.

Table 4: Results regarding green waste gasification and integration with landfill gas

Annual biomass availability	**2013** [44]	**2017** [32]
Wet biomass amount at 39 % moisture [ton]	13300	18294
Dry biomass amount [tons]	8113	11160
Dry biomass heating value [MJ/kg]	18.8	18.8
Gasifier characteristics		
Annual working hours [hours]	7500	7500
Biomass thermal power input [kW]	5649	7771
Syngas total volume V_{syngas} [m^3]	13240416	18213120
Syngas flow rate $\dot{V}_{syngas}$ [Nm^3/h]	1765.39	2428.41
Syngas thermal power P_{syngas} [kW]	3212	4503
Annual biochar production [tons]	162.26	223.20
Power production from the CHP engines		
Gas power input (landfill gas + syngas) [kW]	8528	9819
Electrical output [kW]	3488	4016
Electrical output increase [kW]	1315	1843
Thermal output [kW]	3855	4438
Thermal output increase [kW]	1454	2037

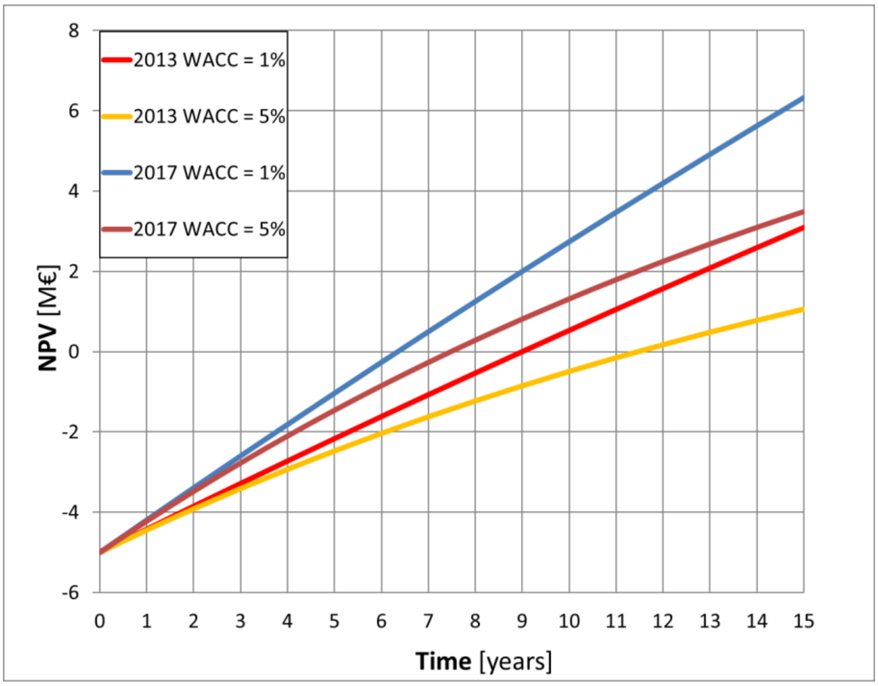


Figure 7: Net present value analysis of the gasifier investment

3.3 Biomass growth rate

To evaluate the biochar enhancing power on basil compared to other substrate types, some growth rate parameters were measured. Basil shoots were harvested after a growth period of 55 days. The germination rate of the seeds, the height and weight (fresh and dry) of the 3 main shoots for each pot were measured, in order to evaluate which substrate type had the best performance on biomass production. Parameter data was collected from 5 pots for each of the 3 substrate types (Soil, Biochar and Compost). Mean values of 5 repeated tests for each substrate type are shown in Table 5 and Figure 8. The dry weight of the plant was obtained by drying the seedlings in a heater at 60 °C for 24 hours [50]. The fresh basil biomass production in the biochar substrate is significantly higher (*p*-value, $p < 0.05$) than in the standard soil and compost. If we evaluate the dry weight, biochar biomass is comparable with soil biomass production, but not with the dry weight of compost biomass, which is significantly lower than biochar ($p < 0.05$). The height of the biochar and control shoots is comparable: 6.07 ± 1.33 cm is the mean value height for biochar seedlings and 6.07 ± 1.42 cm is the mean value height for the control seedlings. The height of the compost plants has a mean value of 4.00 ± 0.25 cm that is significantly lower ($p < 0.05$) than the biochar and the control plants (Table 5). Complete seed germination was occurred in all pot types.

Table 5: Basil physical parameters. Mean value (Av.) of fresh weight, dry weight and height to the 3 main shoots from 5 pots of 3 different substrate types. Fresh weight of produced biomass was measured with and without roots. Roots were cut off at the starting point of the apical basil stem. Standard Deviation (SD) of mean values are reported.

***O. Basilicum* substrate**	**Fresh Weight (g)**	**Fresh Weight no roots (g)**	**Dry Weight (g)**	**Height (cm)**
SOIL Av.	1.59	1.39	0.19	6.07
SD	0.45	0.36	0.06	1.42
BIOCHAR Av.	2.45	2.12	0.24	6.07
SD	0.49	0.45	0.06	1.33
COMPOST Av.	0.90	0.76	0.10	4.00
SD	0.14	0.11	0.01	0.25

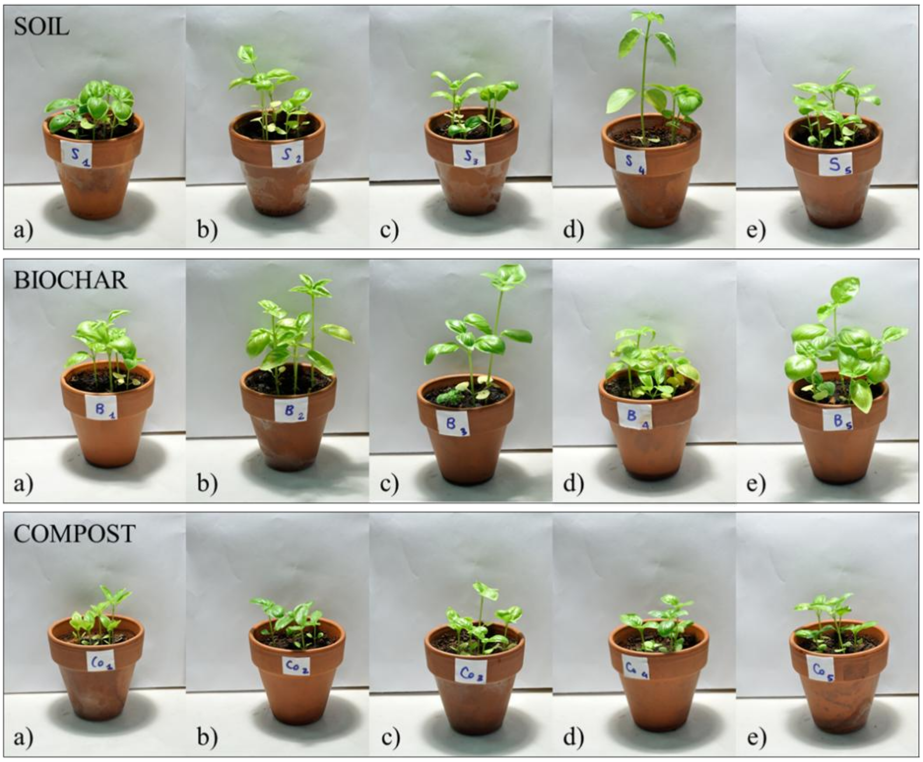


Figure 8. *Ocimum basilicum* after 55 days of experimental trial. Control substrate, soil, soil + 30% w/w biochar and soil +30% w/w compost. Five seeds for each substrate type were planted in 5 pots. The set of biochar pots shows a greater biomass growth.

Soil substrate enriched with 30% biochar showed interesting growth effects on *Ocimum basilicum* growth (Table 6). Biochar recorded significantly better behaviour as amendment for aromatic plant production compared to compost. Plants grown in 30% biochar substrate, without adding any chemical fertilizer into the test pots, exceeded the control plants. Gasification biochar introduces indeed some physical and chemical improvements to soil properties, such as carbon enrichment and nutrient availability enhancement, rising of pH value and helping soil water content [50-54]. These experimental findings lead to the estimation of the potential increase of the cultivations grown by S.A.B.A.R. using biochar as soil amendment. The mean yield of basil production inside the current greenhouse is 70 t/year [44]. Considering the enhancing effects on biomass rate brought by biochar on soil, the fresh basil production could be raised by 53%. Thereby, gasification biochar application to the S.A.B.A.R. greenhouse soil could considerably increase profit.

Table 6: Basil physical parameters. Mean value (Av.) of fresh weight, dry weight and height of the 3 main shoots from 5 pots of 3 different substrate types. Fresh weight of produced biomass was measured without roots. Roots were cut off at the starting point of the apical basil stem. Standard Deviation (SD) of mean values are reported.

O. Basilicum	**SOIL**	**BIOCHAR**	**COMPOST**
Fresh Weight (g)	1.39±0.36	2.12±0.45	0.76±0.11
Dry Weight (g)	0.19±0.06	0.24±0.06	0.10±0.01
Height (cm)	6.07±1.42	6.07±1.33	4.00±0.25

4. Conclusions

An experimental-driven modelling of green waste gasification applied to the S.A.B.A.R. landfill scenario was proven to be an efficient pathway to a better use of this biomass source.Starting from 18294 tons of green waste, it is possible to obtain approximately 18 millions of Nm^3 of syngas every year. Using this syngas as fuel in the existing CHP engines will increase the electrical landfill power production to 1.843 MW adding also 2.037 MW of thermal power. This increased energy yield will be remunerated through subsidies for renewable energy production. In such a way, considering the investment costs of the gasifier 5 M€, the payback time is assessed to be 6 years. In addition, the biochar produced can be used to improve the basil cultivation in the landfill greenhouses. Results show an increase in the basil production using soil mixed with 30% wt. of biochar compared with standard soil. This application can lead to more efficient and sustainable agricultural processes, giving new impulse to bio-energy production and recycling of by-products in a circular economy context.

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*Declaration of Interest Statement

Declaration of interests

☐X 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.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: