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Techno-Economic and Environmental Assessment of Syngas Cleaning Solutions for Bioenergy Generation

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The present paper deals with the process analysis of a biomass-to-electricity industrial plant. Starting from the process simulation by means of Aspen Plus software, this work discusses the technical, environmental, and economic performance of a biomass integrated gasification combined cycle (BIGCC) power plant. To enable a safe integration, a mid-to-high temperature cleaning system has been implemented to target reference inorganic contaminants that hinder the use of syngas in commercial applications, namely hydrochloric acid, and hydrogen sulphide. The actual effectiveness of the overall system has been evaluated by performing a holistic assessment of a 7 MW_e BIGCC using hazelnut shells as biomass and equipped with sorbent reactors to remove the target contaminants before entering the power generation section of the plant.

1. Introduction

Concerns on climate change and supply chain stability are leading to the development and implementation of renewable-based alternatives to the current fossil fuel-based system that provide technological support for the ongoing ecological transition, such as bioenergy. Bioenergy derives from the valorisation and conversion of biomass, a term referred to the biodegradable fraction of products, waste, and residues from biological source. Among the possible biomass valorisation routes, the thermal conversion of waste is highly effective from a technical, economic, and environmental point of view, and it is also considered as an opportunity to implement an integrated waste management system fostering both waste reduction and energy procurement diversification (Barba et al., 2015). The conversion processes different from combustion are commonly referred to as “modern bioenergy” and are considered as pivotal source of renewable energy, with biomass gasification being recognised as one of the most technically mature and environmentally sound biomass conversion process. Gasification is a high temperature thermochemical process that generates a product gas, also known as syngas, that has the potential of partially substituting conventional gaseous fossil fuels in both industrial and energy applications. Apart from the lower environmental burdens if compared with combustion, the development and spread of biomass gasification throughout the last decades has been favored by the possibility of processing different feedstock and integrating this technology in small-to-micro scale solutions such as internal combustion engine (ICE) (Fantozzi & Bartocci, 2017). On the other hand, Biomass Integrated Gasification Combined Cycle (BIGCC) configurations provide a significant advantage in terms of scale-up potential and possibility of retrofitting existing power generation facilities (Baratieri et al., 2009). Nonetheless, the full integration of biomass gasification system is hindered at the technological level by the strict quality requirements of downstream equipment, since their structural integrity is threatened by the presence of undesirable contaminants of inorganic or organic nature in the product gas. The presence of these contaminants, whose concentration is dependent on the chemical composition of biomass, causes issues such as fouling, corrosion, abrasion, poisoning, degradation reactions, etc. (Marcantonio et al., 2021). The removal of tars, typically made up of aromatic hydrocarbons, has been extensively targeted in literature proposing devoted catalytic systems (Volpe et al., 2016). Nonetheless, several processes, operating at different temperatures, have been proposed to target the removal of these contaminants. Among these, the low temperature ones are featured by drawbacks caused by

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tar condensation, while mid-to-high temperatures (400-850 °C) syngas cleaning methods are regarded as the most suitable post-treatment processes due to the possibility of operating at the gasification temperature and significantly reducing the presence of both inorganic and organic compounds in a cost-effective manner by means of sorbent reactors (Marcantonio et al., 2021). However, through the last decades, researchers have been focused on assessing the feasibility of combining BIGCC with carbon capture technologies to implement a negative emission system. The reason behind this is that biomass is considered as a carbon neutral energy source due to the balance between the amount of carbon released during conversion and the amount of carbon absorbed by plants during their growth. Therefore, several investigations have been performed to develop and optimise a proper configuration that could offer a technical and economic advantage derived from the implementation of such integrated systems (Zang et al., 2018). The current requirements related to the ongoing ecological transition call for holistic assessment approaches that effectively embrace and investigate the pillars of sustainable development (beyond the techno-economic evaluation of processes). To this end, a wider use of quantitative assessment methodologies, such as Life Cycle Assessment (LCA), is essential to gain insight into the actual environmental benefits and hotspots related to technological solutions in the context of ecological transition. Moreover, prior to the integration of carbon storage technologies, a deeper understanding of the proper cleaning system to integrate within BIGCC is require operating in a safe manner and extend the lifetime of the overall system. The present study outlines the results of a holistic investigation that has been performed to assess the techno-economic and environmental feasibility of producing electricity by means of a BIGCC with biomass-derived syngas treated to remove sulfur and chlorine derived inorganic contaminants to enable a safe and continuous operation of the gas turbine by ensuring the compliance with the inlet gas quality requirements. The process has been modelled and implemented adopting internal heat recovery strategies and a gate-to-gate assessment has been performed to obtain the actual environmental footprint of the bioenergy thus produced. Eventually, the preliminary estimation of Levelized Cost of Electricity (LCOE) has been assessed and, along with the environmental footprint, compared to a similar scale natural gas combined cycle (NGCC) power plant. The latter has been selected as the benchmark fossil-based technology in Italy, which is the country being selected as reference geographic case study.

2. Materials and Methods

A BIGCC plant equipped with a mid-to-high temperature cleaning process has been developed adopting hazelnut shells as biomass feedstock. The selection of this biomass is related to its peculiar physico-chemical properties and the availability at a regional scale in Italy. From a technical perspective, the use of hazelnut shells as feedstock requires a proper post-treatment process due to the high content of sulfur and chlorine according to the biomass ultimate analysis (Table 1). Moreover, the production of hazelnut in Italy is significant, with nearly 140,560 t produced annually and a value chain that is featured by a significant potential in terms of circular management, with the hazelnut skin (~2 wt. % of the fruit) being rich of polyphenols recoverable through an extraction process (Bertino et al., 2023; Mazzeo et al., 2023) and the hazelnut shell being recognised as a valuable feedstock to produce a good quality syngas in small-case decentralised systems where the residues of nuts are abundant (Dogru et al., 2002). Considering “Lazio” region, in Italy, where the feedstock availability has been estimated to account for approximately 20.02 kt_{dry}/y (Villarini et al., 2019), the biomass flowrate has been set to 3 t/h (corresponding to 17 MW_{th} input to the gasifier) to assess the effects of exploiting the whole regional availability.

Table 1: Physical and chemical properties of hazelnut shells (Villarini et al., 2019)

Proximate analysis (wt. %, dry basis)			Ultimate analysis (wt. %, dry basis)						Other properties		
Ash	Volatile matter	Fixed carbon	C	H	N	O	Cl	S	Moisture (wt. %)	HHV (MJ/kg)	LHV (MJ/kg)
1.16	72.45	26.39	50.38	6.03	0.22	42.32	0.38	0.67	7.9	20.20	18.85

2.1 Process configuration and modelling

The BIGCC plant has been designed as composed of a gasifier, producing syngas from hazelnut shells, coupled with a hot gas cleaning treatment and a power generation unit, consisting of a combined cycle operating at two pressure levels within the heat recovery steam generator (HRSG). The process has been modelled and simulated in Aspen Plus environment, adopting the main outcomes and assumption of our previous study (Marcantonio et al., 2020). As depicted in the flowsheet reported in Figure 1, the HAZELNUT stream enters the DECOMP reactor where the biomass, defined as a non-conventional component, is converted into its constituting components according to the ultimate analysis (Table 1). Then, considering the high chlorine and sulfur that are generated through DECOMP, a block named INPROD has been included to simulate the production of HCl and H_2S. The resulting stream has been therefore split by means of a separator SEP, with the R-FD stream feeding the gasifier (GASIF) alongside with steam, that has been selected as gasifying agent and is produced within the power generation section. The GASIF has been modelled with the restricted quasi-equilibrium approach to ensure an accurate syngas composition conducing the reactions at their Quasi-Equilibrium Temperature (QET). Being the resulting syngas, SYN-2, composed of a high content of HCl and H_2S, a post-treatment section made up of two sorbent reactors, namely DECHLOR and DESULF, respectively equipped with nahcolite ($NaHCO_3$) and zinc oxide (ZnO) as sorbent. The SYNCLEAN stream, cleaned by ash and solid products by means of CYCLONE1 and CYCLONE2, is cooled down and dried before being compressed by means of SYNCOMPR and sent to the BURNER alongside with an air stream, COMP-AIR. The combustion product gas, HOT-GAS, fed the TURBINE to generate power, whereas the FLUE-GAS stream is sent into a double-pressure HRSG for further utilization. The steam turbine cycle is made up of a high-pressure block (HR-HPS and HPTURB) and a medium pressure block (HR-MPS and MPTURB), besides the preheating unit, HR-PRE, that releases the exhaust gas, FLUE-OUT at an allowable temperature.

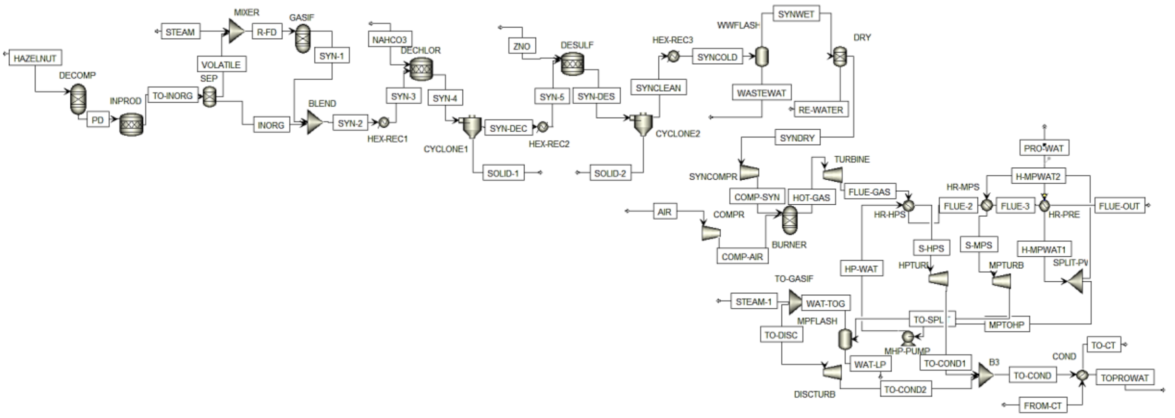

Figure 1: Flowsheet of the plant configuration implemented in Aspen Plus

The gasification section has been designed to operate with a steam to biomass ratio of 0.5 at atmospheric conditions and high temperature (850 °C), while the DECHLOR and DESULF reactors operating temperature have been set at 550 °C and 460 °C, respectively (Marcantonio et al., 2020). The flow rates of nahcolite and zinc oxide have been adjusted to obtain the reduction of HCl and H_2S under 1.5 ppm and 20 ppm (Marcantonio et al., 2020), respectively, enabling the safe operation of syngas in TURBINE. Both COMP-AIR and COMP-SYN enter the BURNER at 15 bar, with the air flowrate being adjusted to ensure a gas turbine inlet temperature of 1200 °C. The double-pressure HRSG has been designed to operate at 100 bar and 35 bar in the high pressure and medium pression section, respectively. The sub-system has been designed aiming at maximizing the heat recovery in HR-HPS by imposing a strict approach temperature at the exchanger outlet. The discharge pressure of the steam turbines has been set at 0.09 bar, with a portion of S-MPS being previously extracted to feed the gasifier at the atmospheric pressure. The outlet streams of HPTURB and DISCTURB are collected and condensed by means of COND, using cooling water at 20 °C deriving from a cooling tower. The isentropic and mechanical efficiencies of the rotating equipment have been retrieved from the literature (Niu et al., 2021). An indirectly heated fluidized bed gasifier, whose thermal demand is partially fulfilled by implementing internal heat recovery strategies, has been selected. The residual thermal demand has been assumed to be covered by an additional use of the feedstock. Therefore, the energetic performance of the plant has been assessed by means of the fuel utilization efficiency (η_f), defined as the ratio between the net energy output of BIGCC (P_{cc}) and the chemical energy contained in the total amount of feeding biomass (M_{haz}), as shown in Equation 1.

$$\eta_f = \frac{P_{cc}}{M_{haz} \cdot LHV_{haz}} \tag{1}$$

2.2 Life Cycle Assessment

LCA is an internationally standardized methodology for the quantitative and holistic assessment of the environmental burdens related to a product, process or service throughout its entire life cycle (The International Organization for Standardization (ISO), 2006). The LCA approach is pivotal to achieve a comprehensive understanding of both the environmental externalities and the eventual burden shifts related to the technological solution under investigation. The goal of the present study is to evaluate the environmental profile of a biomass-based electricity generation system, majorly focusing on the impacts due to the introduction of a post-treatment gas cleaning process to permit the integration between the product gas and the gas turbine. The functional unit (FU) selected for the assessment is the production of 1 kWh of electrical energy at the plant gate, whereas the boundaries of the system have been set adopting a gate-to-gate approach and have been designed to comprise: (1) syngas production and cleaning, and (2) electricity generation. Biomass collection, handling and transportation processes have been neglected in the present study. OpenLCA software has been used for the present assessment employing the ecoinvent database. The impact assessment methodology that has been selected to perform the present investigation is CML, as reported in Zang et al., (2020) and the following impact categories have been considered: climate change (GWP), ozone depletion (ODP), acidification (AP), and depletion of abiotic energy resources (ADP). As for the life cycle inventory stage, the sub-systems have been modelled using data deriving from the process simulation outcomes as foreground data, background data for biomass waste, and market data for the sorbents. Due to the similarities of the investigated plant configuration with the one of the identified benchmarks, the construction stage of the equipment has been neglected.

2.3 Economic Assessment

The Levelized Cost of Electricity (LCOE) has been calculated to assess the economic feasibility of the proposed configuration. The LCOE has been computed according to Equation 2 and indicates the minimum selling price of the generated electricity required to recover investment cost accounting for the operating cost during the plant lifetime.

$$LCOE = \frac{\sum_{t=1}^{t=n} \frac{I_t + FO\&M_t + VO\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{t=n} \frac{E_t}{(1+r)^t}} \qquad (2)$$

where, I_t is the investment expenditures, $FO\&M_t$ is referred to the fix operation and maintenance (O&M) in the year *t*, $VO\&M_t$ contains the variable O&M costs in the year *t*, F_t is the fuel cost in the year *t*, E_t is the energy production in the year *t*, *n* is the lifetime of the plant, and *r* is the discount rate. The macroeconomic assumptions that have been adopted for the present assessment have been gathered from Badouard et al., (2020), whereas data on gasifier capital cost have been taken from (Rajabi Hamedani, 2017), and utilities and reagent costs are based on market data. For the purpose of the present investigation, only the investment costs related to the gasifier and the combined cycle have been considered, adopting a 30% overhead to account for the additional capital investment requirements. The cost of biomass feedstock has been varied in the range 40-75 €/t as reported in (Rajabi Hamedani, 2017). Table 2 lists the main assumptions deriving from literature analysis.

Table 2: Main economic assumptions

Macroeconomic Assumptions					Capital Investment		Market Data				
Capacity factor	Lifetime	Discount rate	FO&M	Interest rate	Gasifier	Combined Cycle	Deionised water	Cooling water	Wastewater treatment	Zinc oxide	Nahcolite
0.7	25	7%	4%	5%	7,800 k€	1,300 €/kW	0.8 €/m^3	0.5 €/m^3	0.3 €/m^3	2.6 €/kg	2 €/kg

3. Results

3.1 Syngas composition and net-energy generation

The 7 MWe BIGCC system has been evaluated in terms of safe operation and overall energy efficiency. The cold syngas composition retrieved by Aspen simulation is reported in Table 3, with the low concentration of HCl and H_2S being achieved by using 24.87 kg of $NaHCO_3$ (per reactor) and 46.98 kg of ZnO (per reactor), respectively. The power efficiency of BIGCC has been computed to be 45.93%, based on gas turbine power (11.57 MW_e) and steam turbine power (2.83 MW_e) and considering the power requirements of both air and syngas compressors (7.18 MW_e). Nonetheless, due to a residual thermal demand of the gasifier of 3.81 MW_{th}, the actual fuel utilization efficiency decreases to 36.96%, considering an additional biomass use of 728 kg/h to provide the needed heat.

Table 3: Syngas Composition

Syngas composition						
H_2 (%wet mole fraction)	CO (%wet mole fraction)	CO_2 (%wet mole fraction)	H_2O (%wet mole fraction)	CH_4 (%wet mole fraction)	HCl (ppm)	H_2S (ppm)
49.16	30.69	8.01	11.86	0.19	<1	<1

3.2 Environmental performance

The results of the LCA, reported in Figure 2, confirms that the BIGCC systems detain a competitive advantage over NGCC plants, leading to 83% reduction in GWP, 90% reduction in ODP, 89% reduction in ADP, and 26% reduction in AP. The cause of the small reduction in AP has been found related to the use of biomass for satisfying the residual thermal heat demand.

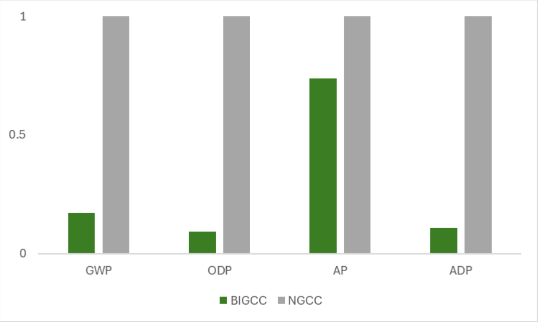

Figure 2: LCA comparison between BIGCC and NGCC.

3.3 Levelized Cost of Electricity

The LCOE related to bioenergy generation by means of the investigated system has been evaluated in the range between 79.78 and 97.86 €/MWh$_e$ corresponding to a biomass cost of 40 and 75 €/t, respectively. Within the same range, the share of LCOE of capital costs varied between 45.1% and 36.7%, whereas the contribution of biomass feedstock varied between 25.9% and 39.6%. The computed value is lower than the 2018 LCOE reported in Lourinho et al., (2023), who indicated 150 €/MWh$_e$, and in line with the cost of NGCC derived electricity (95 €/MWh$_e$).

4. Conclusions

The performance of a 7 MW BIGCC have been investigated adopting a holistic approach to account for the techno-economic and environmental effectiveness of the proposed solution. The gasification section has been integrated with hot gas cleaning process to ensure the safe operation of the downstream equipment and therefore a long lifetime of the plant. The overall efficiency of the plant has been estimated of nearly 37%, considering the residual thermal demand that has not been covered by internal heat recovery strategies. The need for additional biomass intended for heat provision increases the biomass related costs of around 24% and generates detrimental impacts in terms of acidification. On the other hand, the implementation of the cleaning section has not been linked to negative environmental and economic externalities during plant operation. Further investigations are required to assess the effective economic and environmental costs related to biomass collection, handling, and transport to the power generation site. This assessment should account for both regional feedstock availability and potential hybrid solutions employing a mixed biomass feedstock or a blending with natural gas to increase plant capacity and maintain competitiveness.

Nomenclature

E_t – energy production, MWh
F_t – fuel cost, €
$FO\&M_t$ – fix operation and maintenance cost, €
I_t – investment expenditures, €
LCOE – fin length, €/MWh
LHV_{haz}– lower heating value, MJ/kg
M_{haz} – hazelnut flow rate, kg/h
P_{cc} – power capacity, MW
r – discount rate
$VO\&M_t$– variable operation and maintenance cost, €
η_f – fuel utilization efficiency

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