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Life Cycle Assessment of a Wood Biomass Gasification Plant and Implications for Syngas and Biochar Utilization

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Abstract: The growing attention regarding the environmental challenges in the energy sectors pushes the industrial system toward the investigation of more sustainable and renewable energy sources to replace fossil ones. Among the promising alternatives, biomass is considered a valid source to convert the system and to reduce the fossil fraction of the national energy mixes, but its multiple potential uses need an environmental evaluation to understand the actual benefit when it is used as an energy resource. For this purpose, life cycle assessment (LCA) is applied to a wood biomass gasification system aimed to produce electricity and heat generated after the combustion of the produced syngas and the management of the biochar. The aim is to provide a quantitative comparison of (i) a baseline scenario where wood biomass is sourced from waste and (ii) a second scenario where wood biomass is drawn from dedicated cultivation. A further evaluation was finally applied to investigate the environmental implications associated with the biochar composition, assuming it was used on land. The proposed strategies resulted in an environmental credit for both the examined scenarios, but the outcomes showed a net preference for the baseline scenario, resulting in better environmental performances for all the examined categories with respect to the second one. It underlines the potentialities of using waste-sourced biomass. However, according to the Climate Change category, if on-site dedicated biomass cultivation is assumed for the second scenario, the baseline is considered preferable only if the biomass transportation distance is <600 km, which is estimated as a theoretical distance for scenarios to break even. Finally, biochar composition proved a particular concern for toxicity-related categories. This study highlights the importance of applying objective and standardized methodologies such as LCA to evaluate energy production systems based on alternative sources and to support decision-making toward achieving sustainability goals.

Keywords: life cycle assessment; gasification of biomass; biochar use on land; energy from biomass

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1. Introduction

1.1. Energy, Biomass, and Syngas

Rapid population expansion and industrialization over the past few decades have led to a steadily rising worldwide demand for energy [1]. In addition, the unprecedented European energy crisis due to the Russo-Ukrainian conflict further stressed the need to convert energy systems toward decarbonization strategies [2]. Decarbonization, or more extensively, the reduction in the environmental impacts associated with the energy sources, highly depends on a successful replacement of fossil fuels in the electricity grid mix [3–6]. Several research activities have been published or are currently involved in the evaluation of the potential use of biomass, especially as a by-product or waste, to increase the renewable fraction in energy mixes [7–12]. The wood fraction of biomass presents some advantages in terms of availability since the harvested amount is predicted to increase globally from 3.7 billion m^3 in 2010 to 5.7 billion m^3 in 2050 (+54%) [13].

In addition, although biomass combustion generates CO_2, such emissions are, in principle, part of the natural carbon cycle [14]. Both Waste-Wood Biomass (WWB) and Wood from Dedicated Crops (WDC) represent viable options for energy generation through thermochemical and biochemical conversions. WWB is advantageous if the transportation processes associated with its procurement are not excessively costly and if there are no economic and environmental benefits associated with other management strategies [7]. In contrast, WDC is considered feasible only if local resources (i.e., available land area and suitable climatic conditions) allow for its growth, providing a constant and/or programmable flow for the designed system [15]. Typically, a blend of locally cultivated energy crops with imported biomass would constitute a viable strategy, also from the perspective of source diversification [15,16]. Among others, gasification is a promising and efficient way to convert biomass/waste into valuable energy carriers, such as synthetic natural gas [17] or syngas [18–22]. The production and chemical mixture of syngas are dependent on the process conditions, requiring a specific supply of oxygen to yield a fuel gas rich in hydrogen and carbon monoxide and the inflowing biomass. Drawing from dedicated biomass can offer the advantage of controlling the composition of the input WDC.

Syngas can be produced from a wide range of biomass feedstocks, and, to date, it is widely used to produce chemicals [23] or energy since it has a lower calorific value (LHV), which makes it suitable for combustion [24]. As an alternative, many studies investigate its employment as a precursor for chemical products or hydrogen sources, which, however, require the separation between hydrogen and the other components through membranes or similar technologies [25]. In the relevant literature, two main pathways for turning syngas into energy are usually discussed: (1) converting syngas to biogas [26], hydrogen [27], or liquid fuels through fermentation and the Fischer–Tropsch process [28]; and (2) direct use of syngas for power generation [29]. The direct energy production from syngas leads to some advantages, such as the avoidance of a highly energy-intensive process of pressurization, which is necessary when syngas is catalytically converted into chemicals [30].

1.2. Biochar

Biochar is a type of black carbon produced from a carbonaceous material through the application of heat or chemicals [31]. Specifically, biochar can be generated from organic material that has been combusted under low or no-oxygen conditions through thermochemical processes [32]. Biochar is typically distinguished from common black carbon since the former is suitable as a soil conditioner [33]. Some of the demonstrated advantages of using biochar on soil include increased soil pH, improved nutrient retention and cation exchange capacity (CEC), increased soil C sequestration, and many other variables important to soil quality and agriculture [34–37]. In the case where biochar comes from WDC, the use on land (UOL) may serve as a means to return the nutrients to the original soil [38,39]. Biochar has also garnered extensive attention in the remediation of soils contaminated with potentially toxic elements or organic substances, owing to its adsorption properties and straightforward operations [36]. In addition, thanks to its ability to enhance soil's capacity to retain carbon, the UOL of biochar is considered a valid strategy for mitigating the presence of greenhouse gases (GHGs) in the atmosphere [40,41]. Typically, the non-treated biomass disposed on land decomposes quickly, and the CO_2 is released back into the atmosphere. However, by turning the biomass into biochar, the stability of the carbon increases because cellulose and lignin are destroyed, and aromatic structures are formed. Hence, the carbon is stored much longer [42]. In addition to the environmental benefits associated with the UOL of biochar, several economic savings have also been identified [41].

1.3. Life Cycle Assessment

Life cycle assessment (LCA) is among the most inclusive analytical techniques to analyze sustainability benefits and trade-offs resulting from complex systems [43]. Given that biomass gasification stands as a possible, promising strategy to increase the renewable energy fraction within national energy systems [44], LCA has been previously employed to evaluate the resulting environmental implications [45–47], including the valorization of biomass-derived syngas [48], the production of biochar and its UOL [49–53], and general biomass conversion [52,53]. Notwithstanding these research efforts, the number of studies addressing more complex systems involving biomass valorization through gasification for syngas production and its further combustion for the generation of electrical and thermal energy remain little investigated. This study aims to contribute to filling this lack of information by presenting a case study from a full operating system.

2. Materials and Methods

LCA is a methodology standardized by ISO 14040:2006 and ISO 14044:2006 [54,55], and it is structured on four interconnected phases: (i) Goal and scope definition; (ii) Life Cycle Inventory (LCI); (iii) Life Cycle Impact Assessment; and (iv) Interpretation.

2.1. Goal and Scope Definition

The main goals of this study are the following: (i) to provide an environmental assessment of an industrial process involving the gasification of waste biomass and the conversion of the obtained syngas into electricity and heat; (ii) to evaluate the environmental implications of using wood biomass (WB) derived by dedicated forestry in place of WWB; (iii) to estimate the impacts associated to the composition of biochar yield by the system when it is used on land; (iv) to fill the information gap in the literature regarding similar case studies. This study is designed to provide site-specific results structured on primary data directly provided by the company.

The system boundaries of the models include (i) extraction, production, and supply of raw materials and intermediates involved in the production; (ii) generation, supply, and consumption of the energy carriers; (iii) operative phases; (iv) the UOL of the generated biochar and the environmental savings associated to electricity and heat generated, following a cradle-to-grave approach (Figure 1). The contribution of the infrastructure is considered negligible because of its relatively long life span and, therefore, is excluded from this study. Since the system was developed to maintain a fixed WB inflow of 85 kg/h, such a value was selected as the functional unit (FU). The software employed for the modeling and calculations is SimaPro 9.5 [56].

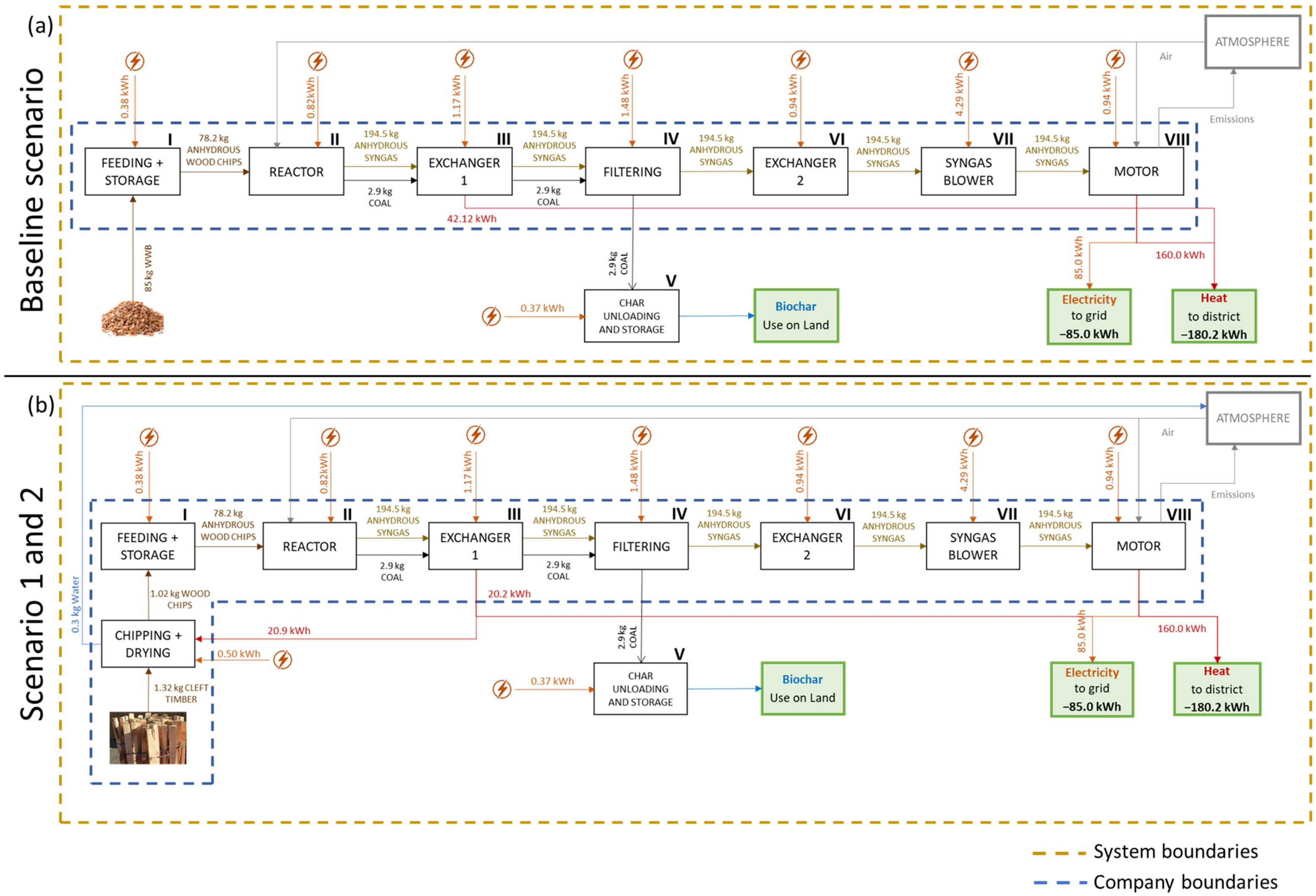

Figure 1. Diagrams representing the baseline scenario (**a**) and scenarios 1 and 2 (**b**). Gold dashed lines represent the LCA system boundaries, while blue dashed lines represent the spatial company boundaries.

2.2. Life Cycle Inventory (LCI)

In this phase, the product system models are created and populated with data related to material and energy flow inventories to provide an accurate and representative system network of the processes involved. The product system is depicted in Figure 1.

2.2.1. General Assumptions

Background processes, such as energy production, water supply to the plant, and raw material production, were obtained from the ecoinvent 3.9 database [57]. Data related to energy consumption and all the involved flows were directly provided by the client as primary information (P.I.). The list of flows is reported in Table S1. The ecoinvent process representing the Italian medium-voltage power generation scenario was modeled according to the latest available year (2022) from the International Energy Agency [58]. The emissions associated with the syngas combustion process were estimated according to the stoichiometry of the reaction. However, such emissions were considered biogenic and equal to the carbon dioxide intake for biomass growth; for this reason, they lead to a neutral carbon balance.

2.2.2. Baseline Scenario

(I) Feeding + Storage

The 85 kg of inflow WWB were assumed to be collected directly on-site, so no impacts from supply were included in the model for the baseline scenario. Further discussion related to the hypothetical impacts associated with biomass transportation is the subject of the sensitivity analysis and will be discussed later on (Section 3.3). In addition, in line with the previous studies [59,60], a "zero burden criterion" was applied to the inflow amount, with the WWB considered waste with negative economic value. Since the WWB was assumed to derive from industrial processes or materials that were already subjected to pre-treatments (e.g., drying) before being employed in this stage, no preliminary steps were required in this scenario. This step required 0.38 kWh_e/FU.

(II) Reactor

The reactor requires 0.82 kWhe/FU to convert 78.2 kg/FU of anhydrous wood chips (AWC) into 194.5 kg/FU of anhydrous syngas (ASG). A constant airflow was also provided, even if it did not affect the environmental burdens since the flowing amount was assumed not to be subjected to composition alterations. The 2.9 kg/FU of non-converted material is conveyed in the form of coal to the Exchanger #1 (III) together with the ASG.

(III) Exchanger #1

The first exchanger removes heat from the ASG inflow, so the mass of the ASG outflow amount is equal to the amount of the ASG inflow. The electricity input of this stage was quantified at 1.17 kWhe/FU, while the removed 41.12 kWht/FU of heat was assumed to be recovered, and it was, therefore, included in the model as an avoided product.

(IV) Filtering

Filtration is applied to separate the 194.5 kg/FU of ASG from the 2.9 kg/FU of coal. ASG is then conveyed to the syngas blower (VII), while coal is directed to Storage (V), waiting to be used on land.

(V) Char unloading and storage

The UOL involves both benefits and burdens to the environment since it stocks carbon in the soil, but it also implies the leaching of metals potentially contained in biochar. The carbon stock also depends on climate and soil conditions [61,62] and carbon content in biochar, which can change as a function of the process (e.g., pyrolysis, gasification, etc.) applied to biomass. According to P.I., supported by the literature information [63,64], an average carbon content of 70% was assumed for biochar, with 10% of it being released into the atmosphere. The carbon content and carbon emissions are both contingent upon the actual composition of biochar, a detail that was not explicitly measured. Nonetheless, this assumption is consistently applied in all the scenarios compared; thus, it does not undermine the validity of the comparisons made. Concerning the metal composition, due to a lack of P.I., the "Agro" limiting metal concentration declared by the European Biochar Certificate (EBC) [65] was taken as a reference for the baseline scenario (Table 1). A complete leaching of the metals listed in Table 1 was considered under a precautionary assumption. Metals were considered to be released in soil in an ionic form [66,67]. The soil sub-compartment selected was "agricultural", considered consistent with the case study.

Table 1. Assumed compositions of biochar for baseline scenario, scenario 1 (EBC Agro), and scenario 2 (EBC AgroBio) reported per ton of dry matter (tDM).

	EBC Agro (g/t_{DM})	EBC AgroBio (g/t_{DM})
Pb	120	45
Cd	1.5	0.7
Cu	100	70
Ni	50	25
Hg	1	0.4
Zn	400	200
Cr	90	70
As	13	13

(VI) Exchanger #2

The second exchanger directs 194.5 kg/FU of ASG to the syngas blower (VII). Also, in this case, no mass losses were considered. Electricity consumption is estimated to be 0.94 kWhe/FU.

(VII) Syngas blower

The syngas blower, with an electricity consumption of 4.29 kWhe/FU, conveys the AG inflow to the Combustion motor (VIII). No mass losses were considered in this phase.

(VIII) Motor

In this phase, 194.5 kg/FU of ASG are combusted to produce 160 kWht/FU and 85 kWhe/FU. Both flows were considered as avoided products and given credit in the model for avoiding, respectively, the production of heat from natural gas and the production of electricity from the Italian national grid mix [58]. The motor requires an auxiliary electricity input of 0.94 kWhe/FU to run the process. As for the Reactor (II), compressed air, which is not predicted to undergo composition alterations, is required. According to Section 2.2.1, the carbon emitted during the combustion phase was considered biogenic.

2.2.3. Scenario 1

The LCI related to scenario 1 was compiled by applying the same assumptions of the baseline scenario, with the exceptions described below.

The main difference is associated with the WDC inflow, which is assumed to derive from dedicated cultivations. The LCI for the cultivation stage was drawn on the ecoinvent database [57]. More specifically, the selected proxy was "Cleft timber, measured as dry mass {CH} | softwood forestry, mixed species, sustainable forest management | APOS, U". Also, in this case, it was assumed on-site cultivation of the biomass, so no transportation burdens were included in this model. The cultivated biomass is then subjected to a drying pre-treatment to remove the excess moisture content. The energy inputs of this phase were estimated according to Havlik et al. (2020) [68], who estimated a flow of 2.9 kWht/kg of evaporated water. Assuming a water content of 23% (P.I.) in the WDC, the resulting heat needed to remove the excess of moisture amounts to 20.9 kWht/FU. In this model, heat supply is assumed to occur from Exchanger #1 (III), ultimately reducing the credit associated with that process stage from 41.12 kWht/FU to 20.2 kWht/FU. After the drying stage, the dried WDC is finally chipped before entering the system. The electricity consumption for the chipping operation is estimated at 0.50 kWhe/FU according to the technical factsheet of the employed machinery (P.I.) and assuming an equipment nominal power of 70 kW and a wood mass flow of 15.75 kg/h [69].

2.2.4. Scenario 2

The LCI related to scenario 2 was created by applying the same assumptions of the baseline scenario. The only difference is associated with the composition of the biochar output (Table 1, second column), which is considered to be the "AgroBio" type instead of the traditional "Agro" in scenario 2. Also, in this case, a complete leaching of the metals is assumed but of lower magnitude consequently affecting the metal concentrations allowed in the AgroBio type.

2.3. Life Cycle Impact Assessment (LCIA)

In the LCIA phase, material and energy flows identified and quantified in LCI (e.g., direct and indirect emissions, energy and resources consumptions, etc.) are converted into potential environmental impacts using well-established cause–effect models. In our analysis, the ReCiPe 2016 v. 1.10 [70] impact assessment method was applied. ReCiPe 2016 provides a comprehensive estimation of the interactions between the system under scrutiny and the environment for a set of 18 midpoint impact categories and three endpoint damage categories.

2.4. Sensitivity and Uncertainty Analysis

The outcomes of the contribution analysis were taken as the reference for setting sensitivity analysis, performed to test the robustness of the model created and enable identification and quantification of the influence of the main exogenous parameters on the environmental impact of the entire system [71].

Furthermore, uncertainty evaluation was performed both for midpoint and endpoint categories by employing the pedigree data quality matrix [72]. More details about data uncertainty are reported in Table S2. As commented earlier, primary data provided by the company were mainly used for the LCA modeling. As such, data are considered very reliable and representative and are characterized by the highest scores for data quality criteria commonly applied in LCA such as, for instance, geographical, temporal, and technological correlations. Conversely, lower data quality scores were assigned to the information gathered from the literature or background data sources.

3. Results

3.1. Comparison between the Three Scenarios

The graphical representation of Figure 2 compares the three scenarios in terms of Climate Change (GWP), showing a net preference for baseline scenarios over scenarios 1 and 2. The negative values are due to the credit attributed to electricity, heat, and UOL of biochar. GWP was selected only for graphic representation, but the whole set of results, including all 18 categories examined and the single score reported in Table S3a,b, shows an evident preference for the baseline scenario for 17 of the 18 examined categories. The only exception is observed for Human Toxicity Potential, carcinogenic (HTPc), where the composition of biochar changes the trend (see Section 3.2). A comparison between the potential impacts estimated for the three scenarios is also reported in Figure S1.

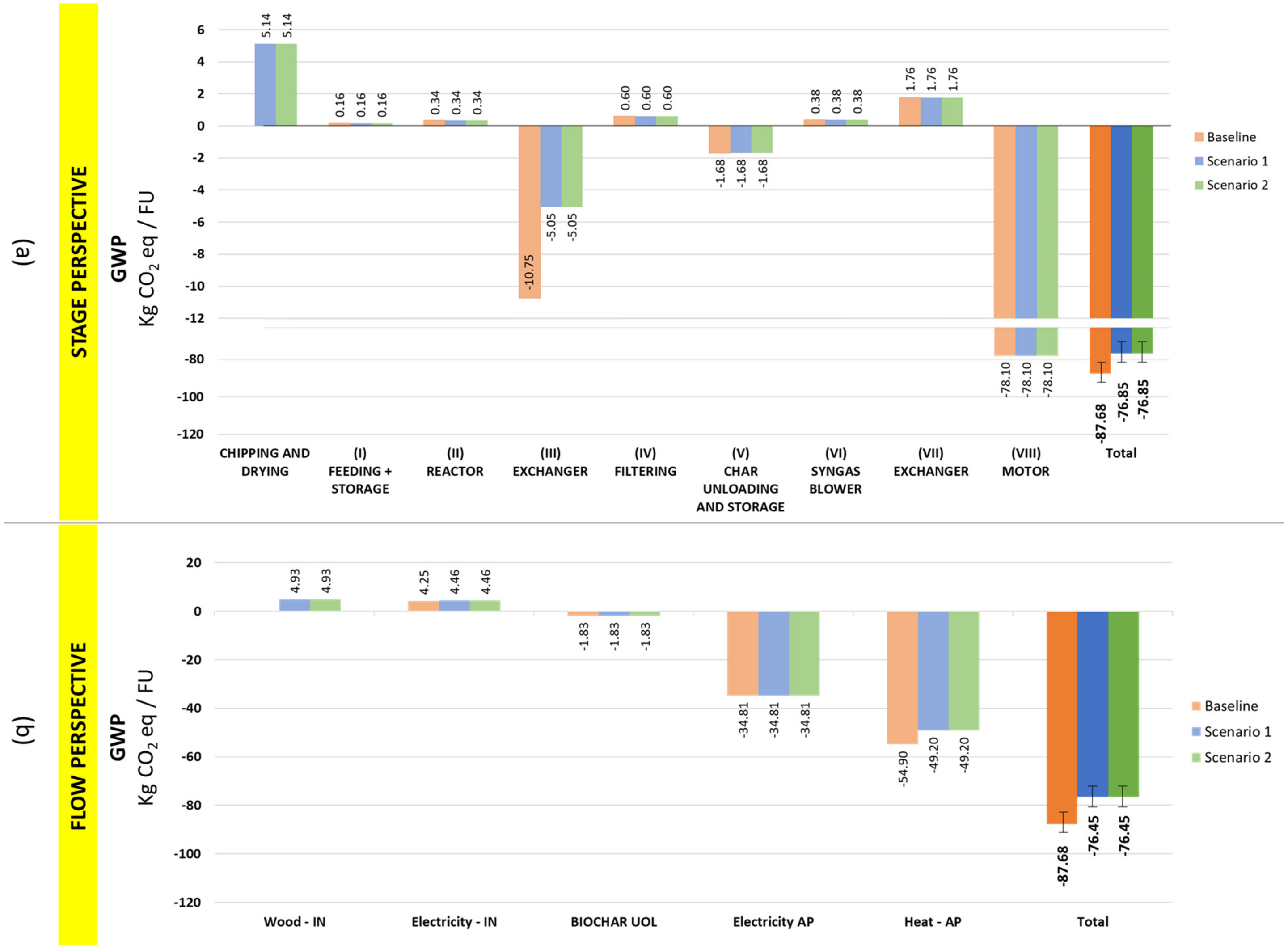

Figure 2. Comparison of the GWP impact between baseline scenario (orange), scenario 1 (blue), and scenario 2 (green). The comparison is provided from a "process perspective" (**a**) and "flow perspective" (**b**). Uncertainty bars are reported in the total values (last columns on the left).

In Figure 2, the results are presented in two forms: process perspective; and flow perspective [60]. The negative values observed for stages (III) and (VIII) are associated with the avoided production of thermal energy and electricity, while −1.68 kg CO_2 eq/FU reported for step (V) is due to the carbon stock in the soil after the UOL of biochar. Regarding direct impacts, the inclusion of chipping and drying stages needed to conditionate the WDC determines the main contributor process for scenario 1 and scenario 2 (61% of the total). However, according to P.I., this step is highly dependent on (i) the moisture of the WDC and (ii) the machinery employed for the chipping (see Section 2.2.3). In particular, drying is responsible for 97% of the GWP impacts associated with the energy consumption of the chipping and drying stages. However, 46% of the GWP impact of scenarios 1 and 2 is observed in the WDC cultivation phase.

3.2. Environmental Impacts Associated with Biochar UOL

The environmental impacts associated with the biochar UOL only regarded five midpoint categories: Terrestrial Toxicity Potential (TETP); Freshwater Toxicity Potential (FETP); Marine Toxicity Potential (METP); Human Toxicity Potential, carcinogenic (HTPc); and Human Toxicity Potential, non-carcinogenic (HTPnc). For the TETP categories, the environmental impact was estimated to be 7.51×10^{-4} kg 1,4 DCB eq/FU for both categories and for this reason, it was excluded from further result elaboration. The environmental impacts observed for the remaining four midpoint categories analyzed and the single score are depicted in Figure 3. The main contributor to the biochar UOL for TETP, FETP, METP, and HTPc categories resulted in the release of zinc cations (II) in soil, while for HTP, the main released cation was Ni (II) (higher than 68% of the total for both Agro and Agrobio). More details about the contribution analysis of biochar are reported in Table S4.

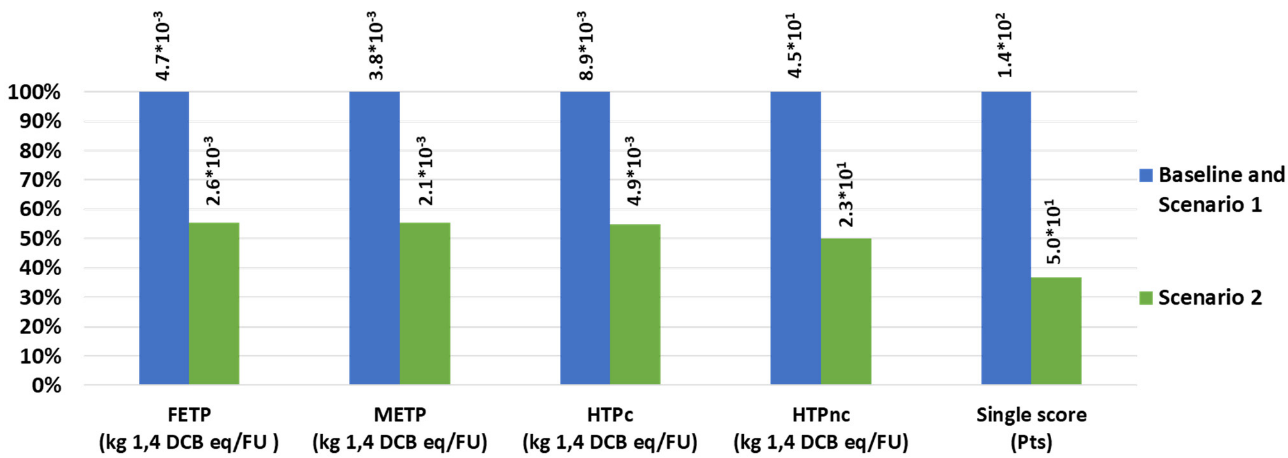

Figure 3. Comparison between the environmental impacts associated with biochar UOL observed for baseline scenario (and scenario 1) and scenario 2, according to the following categories: FETP, Freshwater ecotoxicity; METP, Marine ecotoxicity; HTPc, Human carcinogenic toxicity; HTPnc, Human non-carcinogenic toxicity; and single score.

3.3. Sensitivity Analysis on Transportation

For all the scenarios, WWB and WDC were assumed to be directly collected on-site, so no transportation burdens were calculated. Unlike WDC, which is cultivated in situ by the company, this assumption may not be necessarily applicable to WWB, as this might require acquisition from third parties and supply over several kilometers before reaching the gasification plant. In line with the sensitivity analysis conducted by Arfelli et al. [7], we determined the theoretical minimum distance necessary to balance the GWP burdens between the baseline scenario and Scenario 1. Initially, we computed the disparity in GWPs between the two scenarios, yielding 10.84 kgCO_2 eq/FU. Subsequently, assuming an impact of 0.21 kgCO_2 eq/tkm [57], we calculated the quantity of tkm required to bridge the gap between the two scenarios, resulting in 50.59 tkm. Such value was finally divided by 0.085 t of inbound wood (i.e., the FU) and obtained a breakeven distance of about 595 km. In other words, from a GWP perspective, it is preferable to use WWB instead of WDC until WWB is supplied over a theoretical distance of 595 km. The set of equations is reported in Equations (S1)–(S3).

3.4. Sensitivity Analysis on the Electricity Mix

The energy mix used to model inflow electricity flows is reliable as it is based on the latest available information from the IEA website [58]. However, the decision to allocate the same mix to the electricity credit may be deemed too conservative, as recent methodological advancements suggest that considering only the fossil fraction is more appropriate for simulating the environmental impacts of avoided energy [73]. Therefore, a sensitivity scenario was developed where the renewable fraction was entirely removed from the avoided energy mix, aiming to identify the potential gain in terms of GWP by subtracting only the fossil fraction from the initial mix. Excluding the imported fraction, the Italian electricity mix is constituted of 10% of carbon-sourced electricity, 48% of natural gas-sourced electricity, and 5% of oil-sourced electricity (a total of 63%). By assuming that the whole electricity produced by the examined system would entirely replace the fossil fraction, proportionally, the avoided impact would increase from 34.8 to 56.3 (+38%). More details are reported in Figure S2.

4. Discussion

As mentioned, the absence of recent studies related to systems similar to (or comparable with) the one analyzed in terms of territorial context, applied criteria, input materials, and products makes it difficult to compare the obtained results with benchmarks and relevant findings. A recent article compared two cotton-derived biomass conversion alternatives based on pyrolysis and gasification systems from both economic and environmental perspectives, finding advantages and disadvantages for both configurations. The obtained GWP value (i.e., 108 kg CO_2 eq/kg_{input}) deviates from our outcomes, mainly because of the neglect of credits associated with the avoided production of electricity and the high impacts related to cotton cultivation and harvesting. In addition, the impact assessment method does not correspond to ReCiPe 2016 used for this case study. Zang et al. (2020) [74] evaluated different system configurations to produce energy from biomass via gasification from a life cycle perspective. However, the criteria applied (e.g., system boundaries and credits associated with the avoided products) do not allow for a proper comparison of the results.

The sensitivity analysis underlined that preferability for the baseline scenario (i.e., for the WWB instead of WDC supply) is highly dependent on the distance covered by freight trucks, especially for GWP. This emphasizes the need to consider and optimize the logistic aspects when the intention is to valorize waste since, once a certain distance threshold is surpassed, its sourcing may not be environmentally advantageous, and waste recovery may become less sustainable than in situ biomass production. Once it is established that biomass as an energy source requires attention to the logistical phase, either in scenario 1 or in a hybrid scenario where WDC is integrated with cultivated biomass, it is emphasized that among the advantages of this choice it emerges the possibility of scheduling biomass cultivation based on the predicted energy demand [75].

Regarding the energy aspects, some assumptions pertinent to the calculation of the outcome may be debatable. In particular, the composition of the avoided electricity mix, from which the process was modeled to estimate the savings associated with the electricity credit, is particularly significant. This is because the avoided electricity constitutes approximately 39% of the savings for the baseline scenario. In the recent literature, the avoided GWP was estimated by assuming that the avoided electricity would be produced by the national mix. In previous studies, the energy mix of avoided electricity has been considered identical to the national real mix [7]. However, by conservatively assuming the replacement of the national mix in its actual composition (including renewables), a paradox was indeed reached, whereby an increase in renewable share in the national mix would lead to reduced impacts associated with the production of avoided electricity. It can be inferred that this assumption overlooks the fact that the growth in the share of alternative energy sources to fossil fuels (e.g., from gasified biomass) would replace the fossil fraction and not the renewable fraction. In consistency with recent methodological developments [73], it is suggested to assume the replacement only for the fossil sources, thus more accurately reflecting the real-life scenario, although, perhaps, in a less conservative way. This rationale does not pertain to thermal energy production, as a primary assumption had already been established for natural gas production.

In the relevant literature, the biochar UOL presents both positive and negative arguments regarding its potential environmental impacts [76] or benefits [37,41,77]. Several studies have quantified the potential impacts of the UOL of different biobased materials (e.g., digestate, manure, etc.) [78], but the actual contribution of biochar remains unclear since it presents an intrinsic and characteristic content of pollutants depending on the WDC input and system settings. In this context, by focusing on the cultivation phase of the WDC, the composition of the biochar can be controlled. Such control becomes more complicated when considering energy production from WWB (baseline scenario). However, to date, the settings in the system object of this study, are directed toward maximizing energy production per unit of biomass, consequently leading to a notable reduction in the mass of biochar. Given the mentioned lack of primary information about the impact contribution of the UOL process as a function of the biochar composition, scenario 2 was modeled assuming that the biochar matched the composition limit in organic cultivation (i.e., AgroBio) by "The European Biochar Certificate" [65]. Although this comparison should be intended as a first attempt, it allows for the identification of environmental categories likely affected by the change in composition, emphasizing the need for particular attention to categories addressing toxicity (i.e., FETP, METP, HTPc, and HTPnc). In general, there is considerable debate regarding the potential contamination of biochar with leachable metals, which adversely affect the toxicity parameters in LCA [79]. The presence of metals is closely linked to the feedstock from which the biochar is derived.

Also, it has been highlighted that biochar possesses the peculiarity of being able to capture heavy metals, preventing their leaching [80]. In addition, in the case of WDC and in situ burning, it can be assumed that the contained heavy metals could undergo a stationary bio-geochemical cycle: that is, heavy metals are (i) absorbed in the biomass during its growth and then (ii) released during the UOL of the biochar, with consequential no net-addition of elemental mass to the soil. However, the chemical form of heavy metals concentrated into biochar may differ compared with their initial chemical form, as well as their bioavailability and toxicity [81–83]. The purpose of this study is not to exacerbate the debate but to draw attention to the categories potentially affected by the possible presence of metals, which will need to be investigated and evaluated on a case-by-case basis based on primary information.

The impact of zinc, especially concerning the HTPnc category and, in particular, the endpoint of "human health", has been proven to be cytotoxic and responsible for interfering with the human uptake of copper [84]. In the future, once the effect of biochar UOL is clarified, the attention of the system could be balanced between energy optimization and biochar production.

5. Conclusions

In this study, LCA is applied to a biomass gasification plant aimed at generating electricity and heat from the syngas produced. The environmental quantitative assertion allowed for the comparison of impacts associated with various configurations of the industrial plant, and certain patterns can be summarized as follows. First, due to the credits associated with electricity production, the environmental impacts resulted in negative values for all 18 evaluated categories. Second, the decision to utilize woody biomass derived from waste has proven advantageous compared to utilizing biomass from dedicated crops. Particularly in the case of the Climate Change category, this assertion holds up to an indicative transport distance limit of the input biomass of 595 km. Third, the impacts related to biochar use on land are dependent on its carbon content and elemental composition, yet the potential influence of metal presence on toxicity-related impacts can be discerned. Overall, the ability to produce electricity from syngas, especially if derived from waste ligneous biomass, may serve as an effective strategy to mitigate the environmental impacts of the energy mix and address decarbonization. In this context, LCA effectively allows for the estimation of potential environmental implications associated with various industrial systems, thereby enabling the inclusion of both environmental advantages and disadvantages related to different plant configurations and strategic choices.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en17112599/s1, Table S1: List of the flows involved in the examined system (LCI); Table S2: Scores are assigned with the pedigree matrix to each specific flow and standard deviation calculated per each flow; Table S3a,b: Life Cycle Impact Assessment of the three scenarios estimated for the 18 ReCiPe midpoint categories and Single Score; Table S4: Hotspot analysis related to the biochar UOL; Figure S1: Life Cycle Impact Assessment of the three scenarios estimated for the 18 ReCiPe midpoint categories and Single Score; Figure S2: Comparison between the GWP of the baseline scenario (GWP) and the GWP by assuming that the electricity avoided would be completely derived from fossil resources (GWPfossilAP); Equations (S1)–(S3): Sensitivity analysis related to the inbound transportation of wood.

Author Contributions: Conceptualization, L.C. and C.T.; methodology, F.A. and L.C.; software, F.A.; validation, L.C. and F.P.; formal analysis, F.A.; investigation, F.A.; resources, L.C. and C.T.; data curation, C.T. and F.A.; writing—original draft preparation, F.A.; writing—review and editing, L.C. and F.P.; visualization, F.A.; supervision, F.P.; project administration, F.P. All authors have read and agreed to the published version of the manuscript.

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