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Carbon Balance of a Waste Biomass Supply Chain: The Integration of a Pyrolysis-Based Valorization Process

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In the present work, the valorisation of waste biomass (olive wood) was analysed from an environmental standpoint. A process of thermo-catalytic reforming in which bio-char, bio-oil and syngas are produced, have been integrated to olive wood waste supply chain. In particular, the energy efficiency evaluation was carried out by solving energy and mass balances on the system. Furthermore, the capacity of the systems in energy-self-sustainability has been evaluated along with thermal recovery methods and different uses for the products obtained. The entire supply chain was examined in order to identify its optimal configuration, minimizing environmental charges. Environmental performance is assessed by considering greenhouse gases (GHGs) expressed in terms of CO_2 equivalent as an indicator: this approach allows to define the supply chain incidence on the global warming relative to each of the phases involved in the process. In order to obtain the better configuration in terms of thermal and electrical power for the self-sustainability of the process, and also in terms of CO_2 emission, different scenarios for the use of the products obtained by the process were evaluated. The results have shown that it is possible to self-sustain the process through the proper use of the products. The right combination of use of syngas, bio-oil and char allows to satisfy the thermal and electrical demands of the system by avoiding the use of the energy by the grid. In addition, the choice of the optimal configuration for the use of the products (e.g. use of gas in a cogeneration plant and use of char to field as fertilizer) allows reducing environmental impacts by reducing CO_2 emissions and making the whole process eco-friendly.

1. Introduction

Today, the efficient and sustainable use of resources for energy purposes is a crucial point for tackling energy challenges and combating climate change. In a historical period in which the availability of fossil fuels decreases more and more, bio-wastes such as manure, paper waste, or wood waste, are an important source of renewable energy, and their importance has increased significantly over time. Renewable energy can be produced from a wide variety of sources including wind (Lande-Sudall et al, 2018), solar (Mirza et al., 2018), hydro (Rubes et al., 2018) and (Yuksel et al., 2009) and biomass (Ko et al., 2018) and (Gwak et al., 2018). In particular, the biomass represents an abundant carbon-neutral renewable resource for the production of bioenergy and biomaterials (Baniasadi et al., 2016). It is possible to distinguish biomass in "waste biomass", such as forest and wood residues, or agricultural by products and agro-industrial residues, and "energy crops", i.e. biomass whose cultivation is aimed at the production of energy vectors (Mantineo et al., 2009) and (Amaral et al., 2017). Processes for biomass to energy-valuable products are innumerable and efforts in recent years have focused on refinement of techniques, such as pyrolysis (Paolucci et al., 2016) or gasification (Heo et al., 2010), to increase their efficiency and selectivity towards the products; Advances on waste valorisation: new horizons for a more sustainable society. In particular, recent studies report interesting results about the valorisation of waste biomass starting using a technology based on a thermo-catalytic reforming (TCR) process (Conti et al.2017). The innovation of this technology does not only concern the reactor operating conditions (atmospheric pressure and low temperatures) but especially regards the possibility to obtain, from the waste biomass, three different

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products: bio-char, bio-oil and syngas. To date, literature data shown results about the performance of this technology for a laboratory scale plant of 2 kg h^{-1} (Conti et al., 2017). In this work it was investigate the performance of the TCR technology for a possible scale up of the plant, of about 30 kg h^{-1} of capacity. Therefore, considering the innovation and the yields of the TCR process, in this work the valorisation of a waste biomass (olive wood, Jager et al., 2016) was analysed from an environmental standpoint. The aim of this work is to investigate a possible supply chain configuration for the TCR valorisation process and evaluate all the performance in terms of CO_2 emissions. The environmental performance is assessed by considering the carbon dioxide emissions (fossil and biogenic) at each step of the supply chain, as indicator of the incidence on the global warming of the system under analysis. In order to obtain the best configuration in terms of thermal and electrical power supply also in terms of CO_2 emission, different scenarios for the use of the products obtained were analysed. The capacity of the system in energy-self-sustainability has been evaluated along with thermal recovery methods and different uses for the products.

2. Methodology

2.1 Thermo-catalytic reforming technology for the waste olive wood valorization

The TCR technology consists in an intermediate pyrolysis reactor connected to a reformer (Neumann et al., 2015). In particular the innovative features (of this technology are the coupling between a pyrolysis step (at 400°C) and a catalytic reforming step (at 700°C), and the use of the solid product (char) as a catalyst (autocatalysis).

The main stages of the process are:

(1) “thermal drying”, where the wet biomass is dried to 10-30% moisture content;

(2) “thermal decomposition”, where the dry biomass is carbonized to bio-char at intermediate temperatures (400-500°C) and volatile organic compounds are extracted;

(3) “catalytic reforming”, where through catalytic functions the organic compounds are cracked to quality fuel gases and oils;

(4) “products treatment” where the liquid compounds are condensed and separated into oil and water fractions.

At laboratory and pilot scale, the reactor is heated externally by electrical heating bands (Neumann et al., 2015). More details about equipment configuration can be found elsewhere (Neumann et al. 2015) for a laboratory scale plant (2 kg h^{-1}). In the present work, the same process configuration was considered for a possible scale up of the plant to a production scale of 30 kg h^{-1}.

In order to evaluate the performance of the process in terms of biomass conversion yield and of energy consumption, the mass and energy balances of input dry biomass were solved. The characteristics of the biomass are available in literature, and are summarized in Table 1 (Jager et al., 2016). The collected biomass was considered to be representative of woody residues produced from pruning of agriculture lands. In order to use this biomass in TCR technology, it would be necessary to pelletize, obtaining a diameter equal to 6 mm and a length equal to 10-25 mm (Jager et al., 2016).

Table 1: Composition of waste olive wood (biomass input) and obtained products.

Properties of the stream	Biomass input	Bio-char	Bio-oil	Water	Syngas	
C [wt%]	40	84	75.2	2.3	C_XH_Y [vol%]	2
H [wt%]	70	1.2	7.4	12	CO_2 [vol%]	27
O [wt%]	51	1.5	14.9	86	CH_4 [vol%]	11
N [wt%]	0.36	0.8	2.2	-	CO [vol%]	15
S [wt%]	0.05	0.1	0.3	-	H_2 [vol%]	33
Ash [wt%]	2	12	0	-	-	
Moisture [wt%]	20	0.4	8.2	-	-	
Higher Heating Value HHV [MJ/kg]	17	30.3	33.6	6.21	14.8	
T [°C]	25	700	10	10	10	
Mass flow rate M [kg/h]	34	6.01	1.2	5.05	17.63	
E=M·HHV [kW]	157.8	50.54	11.16	-	72.5	

2.2 Proposed configuration for the olive wood supply chain and possible use of the products

In this paragraph, the possible structure of the supply chain for waste olive wood valorisation is described. Within the supply chain proposed in this work, processes having a clear effect on the environmental impact have been considered. A schematic representation of the supply chain studied is depicted in Figure 1.

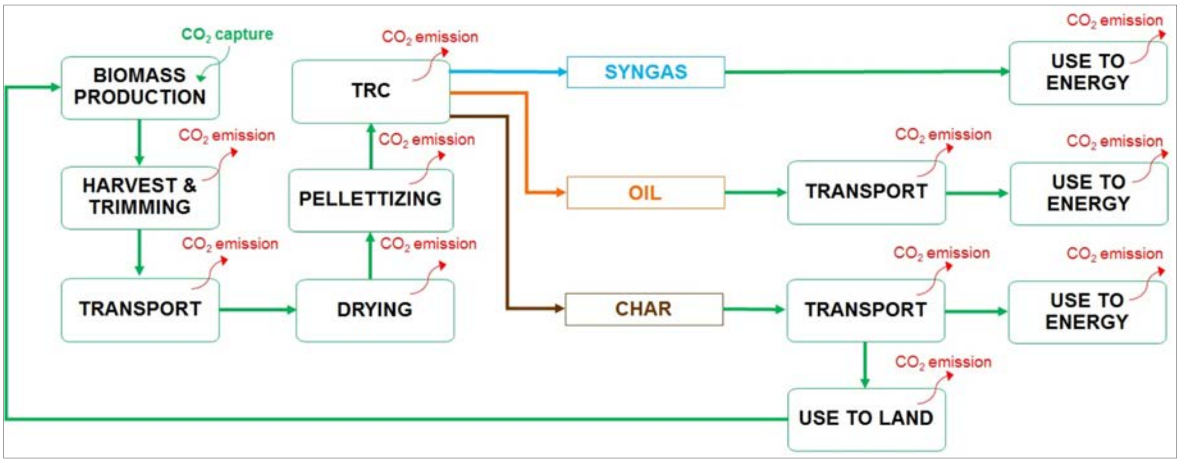

Figure 1: Structure of the olive wood supply chain analysed.

As it is possible to observe from Figure 1, the supply chain has been schematized considering: the collection and pruning of waste olive wood, the necessary pre-treatment (drying and pelletizing) and the use of biomass in the TCR, including the possible scenarios for the use of products and their transports. The production phase of biomass (including cultivating machinery, use of plant improvers) has not been allocated in this supply chain. As it is shown in Figure 1, the possible different uses in-site or out-site of the products were considered. In particular, with the aim to study the energy self-sustainability of the plant, different products use scenarios have been defined, which differ according to the amount of syngas, bio-oil and bio-char used for energy purposes or for other uses (sale of bio-char and energy from bio-oil, or use of bio-char to land). The different uses of the products considered in the supply chain study have an impact both on the energy self-sustainability of the plant, both on the environment in terms of CO_2 emission. In particular, it was evaluated the thermal and electrical power obtained from the use of the products. The complete combustion of the products, or the possible use of the syngas in a cogeneration plant (CHP), was considered. This last alternative allows to obtain both thermal and electric energy from the use of syngas. In particular, the cogeneration plant considered in this study (Cp Series Yanmar) has a thermal and electrical efficiency equal to 52% and 32%, respectively.

2.3 Environmental analysis

The data, in terms of CO_2 emission, as well as inventories for utilities and road transport, and the emission factors were obtained by the European reference Life Cycle Database (ELCD, 2016) and Ecoinvent Version 2 database (Frischknecht et al. 2005). As regards the analysis of environmental sustainability, the most important environmental concern for an energy supply chain is represented by the contribution to global warming associated with the emission of greenhouse gases. This aspect is of great importance in the analysis of alternative energy production systems, as in the present case. For these reasons, the environmental performance is assessed by considering as indicator the emissions expressed in terms of kg of CO_2 equivalents. This approach allows to define the incidence of the supply chain on global heating, for each phases involved in the process. For each phase considered in the olive wood supply chain, it was possible to identify a fraction of "biogenic" CO_2 emission and a fraction of fossil CO_2. In the final balance of CO_2 emissions, the CO_2 captured by photosynthesis is still taken into account. This voice is inserted into the cultivation process and it has negative value (Stoppato, 2013). In fact, this process is based on the concept that the storage kg of CO_2 depend on the kg of dry substance contained in the cultivated biomass (Stoppato, 2013). The CO_2 emissions have been calculated taking into account the time needed for collecting biomass, so considering the operating hours of the machinery used during the process, and also taking into account the operating hours of the TCR plant. Regarding transport, the distance that the truck must travel to transport the biomass and the products to sites of interest were examined. CO_2 emission factors were obtained from descriptive data sheets of Ecoinvent and ELCD databases.

3. Results and discussions

3.1 Analysis of energy self-sustainability

From the mass and energy balances (Jäger et al., 2016) it was possible to determine that the thermal power required by the plant (30 kg h^{-1}) is equal to 16.5 kW (dryer unit) and the electrical power is equal to 37 kW (TCR and condensing unit). The pelletizing machine required 11 kW of electrical power (Nova Pellet). Taking into account these energy requests, the amount of thermal (or electrical) energy that can be obtained from the complete combustion of the products, or from the use of syngas in a cogeneration plant, was evaluated. In particular, the scenarios considered were: Scenario 0 where all the products are available for external supply chain purpose (energy use); Scenario 1 where syngas and bio-oil available for e external supply chain purpose (energy use) and bio-char is used in agriculture; Scenario 2 syngas combustion for heat generation used for the plant. Bio-oil is available for external supply chain purpose (energy use) and bio-char used in agriculture Scenario 3 where syngas is used in CHP plant. Bio-oil is available for external supply chain purpose (energy use) and bio-char is used in agriculture. These first two scenarios provide the external use of the products (such as the possible sale of bio-char, syngas upgrading and bio-oil recovery) and they can be considered as reference configurations because they provide for the use of heat from the grid to meet the plant's energy requirements. The results are reported in Table 2.

Table 2: Possible use of the products obtained from waste olive wood TCR treatment.

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Syngas	EU (100%)	EU (100%)	HG (31%) EU (68%)	HG+EG (47%) EU (53%)
Bio-oil	EU (100%)	EU (100%)	EU (100%)	EU (100%)
Bio-char	EU (100%)	TL (100%)	TL (100%)	TL (100%)
Electric Power [kW] ((-) from grid)	(-) 37 * (-) 11 **	(-) 37 * (-) 11 **	(-) 37 * (-) 11 **	(-)19 * (-) 11 **
Thermal Power [kW] by natural gas ((-) from grid)	(-) 16.5	(-) 16.5	(-) 0	(-)0

Where:
EU: External Use; TL: To Land; HG: Heat generation; EG: Electricity generation;
*Electricity for TCR; ** Electricity for Pelletizing machine.

From the Table 2, it is possible to observe that the best scenario is represented by the Scenario 3, which provide the use of syngas in a CHP unit, and it has two advantages: the possible recovery of thermal energy to be supplied to the plant and also the electricity production, necessary for the TCR reactor. In fact, in this case the electric power from the grid is only 14 kW for the TCR reactor (instead of 37 kW) and 11 kW for the pelletizing machine.

3.2 Results of analysis of CO_2 emission for olive wood supply chain

The different scenarios designed to assess the energy self-sustainability of the plant have different effects also in terms of CO_2 emissions. The environmental impact assessment in terms of CO_2 emissions has therefore been carried out for all the scenarios studied, since they provide for a different use of energy resources taken from the grid and the individual products obtained from TCR. As mentioned above, the global CO_2 balance analyzed for the entire supply chain takes into account biogenic (for example, obtained from the use of biomass or renewable fuels) and fossil CO_2. For each production process considered within the olive wood chain, the CO_2 emission results (Fossil and Biogenic) [kg/year] are reported in the following Tables.

Table 3: Fossil CO_2 emissions [kg of CO_2].

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Harvesting	2.0E+03	2.0E+03	2.0E+03	2.0E+03
Drying	2.7E+04	2.7E+04	0.0E+00	0.0E+00
Pelletizing	1.4E+04	1.4E+04	1.4E+04	1.4E+04
TCR	1.6E+05	1.6E+05	1.6E+05	8.2E+04
Transport	7.5E+03	6.4E+03	6.4E+03	6.4E+03
Total	2.1E+05	2.1E+05	1.8E+05	1.0E+05

Table 4: Biogenic CO_2 emissions [kg of CO_2].

	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Drying	0.0E+00	0.0E+00	3.7E+04	4.4E+04
Pelletizing	9.2E+02	9.2E+02	9.2E+02	9.2E+02
TCR	0.0E+00	0.0E+00	3.7E+04	4.4E+04
Use of bio-char to land	0.0E+00	7.7E+03	7.7E+03	7.7E+03
External use (for energy)	3.0E+05	1.5E+05	1.1E+05	1.0E+05
Photosynthesis	-4.1E+05	-4.1E+05	-4.1E+05	-4.1E+05
Total	-9.8E+04	-2.4E+05	-2.4E+05	-2.5E+05

The results of the global balance of CO_2 emission calculated for the different scenarios, in the case of the olive wood supply chain, are shown in Figure 2.

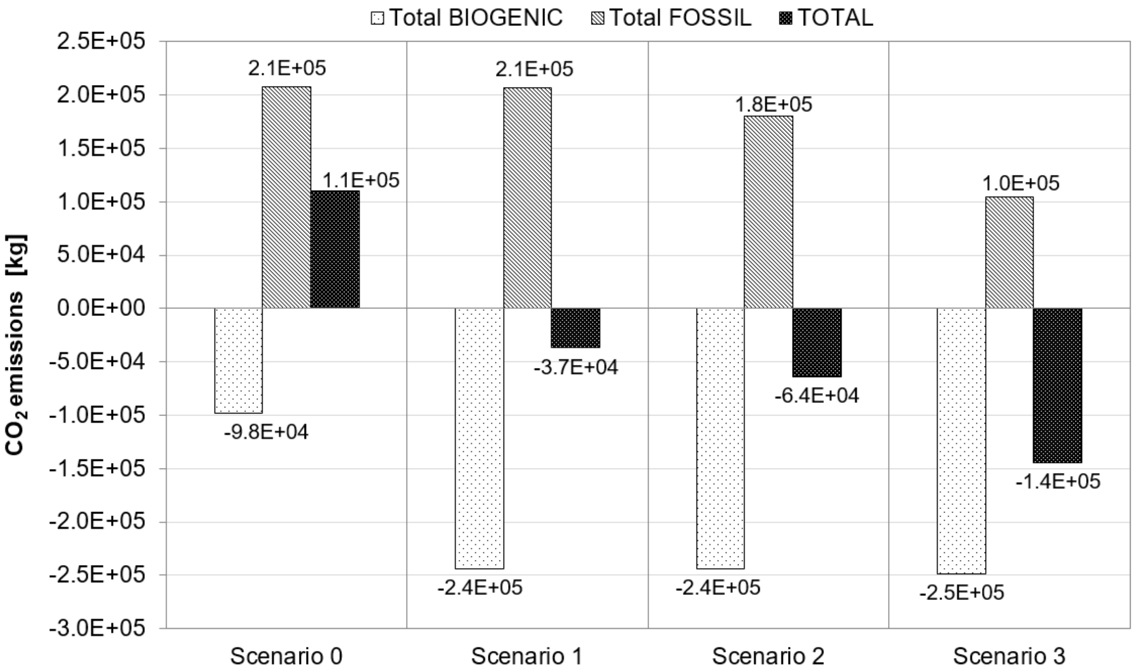

Figure 2: Results in terms of CO_2 emissions for the different scenarios.

As it is possible to observe, Scenario 1 differs from Scenario 0 for the use of bio-char in agriculture, which is the most realistic solution because it allows to reduce CO_2 emissions into the atmosphere thanks to the its characteristics of adsorption also reported in literature (Vochozka et al, 2016). This bio-char feature allows CO_2 to be retained in the soil, which is not released into the atmosphere, thus reducing the total CO_2 emission contribution. However, also in this case the best scenario is represented by Scenario 3, in particular because the CO_2 emissions are the lowest compared to those obtained with the other scenarios (1.0E+05 kg of CO_2).

4. Conclusions

In this study, the performance of a system based on the thermo-catalytic reforming technology was analysed for the valorisation of olive wood waste biomass. It was possible to observe that the different scenarios designed to assess the energy self-sustainability of the plant have different effects also in terms of CO_2 emissions and it was possible to note that among the main phases considered in the supply chain, the most onerous process is represented, in addition to the TCR, by the pre-treatment of biomass. This phase includes both drying and pelletizing. As regards the products (syngas, bio-oil and bio-char), the choice to use them for energy purposes external to the supply chain (power supply to the grid) results in a worsening of the environmental impact in terms of CO_2 emissions.

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