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# TECHNO-ECONOMIC AND ENVIRONMENTAL SUSTAINABILITY OF BIOMASS WASTE CONVERSION BASED ON THERMOCATALYTIC REFORMING

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## ABSTRACT

The development and design of innovative biomass waste to energy conversion processes is a key issue to pursue the implementation of circular economy and to endorse a sustainable management of agricultural land. Assessing the environmental and economic sustainability of such processes is of paramount importance to prevent the trade-off of their impacts. The present study focused on a novel biomass waste to energy conversion process based on thermocatalytic reforming (TCR). Two different agricultural waste substrates (olive wood pruning and digestate) were selected as reference cases for conversion to energy and valuable material fractions. Mass and energy balances allowed the calculation of environmental and economic indexes considering alternative scenarios for the final use of the energy and of the products obtained from the TCR conversion (i.e. syngas, bio-oil and bio-char). A sensitivity analysis was carried out to assess the robustness of results. The overall performances of the TCR process resulted strongly related to the characteristics of the biomass waste and to the possible use of the product fractions obtained in the TCR process. The use of bio-char for soil amendment, allowed by the high quality of bio-char obtained from the TCR, was a key point to improve the expected environmental and economic sustainability of the conversion process.

**KEYWORDS**

Biomass waste; waste valorization; Thermo-Catalytic Reforming; waste to energy

## 1. INTRODUCTION

The production of energy from renewable resources is increasing worldwide, in the framework of low-carbon economy implementation (European commission, 2011; International Renewable Energy Agency (IRENA), 2018). Since 2010, approximately 50% of total primary energy production from renewable sources was generated worldwide using biomass converted to energy either directly, in the form of wood and biomass waste, or by derived products, such as biodiesel or biogas (EIA, 2017). These figures are even higher in the EU-28, where about 65% total primary energy production from renewable sources has this origin (European Commission, 2017).

There is a large variety of biomass materials that can be used for bioenergy production: e.g. wood and wood waste, the organic part of both municipal solid waste and industrial waste, sewage and manure, crop plants and plant by-products of food production (Patel et al., 2016; Li and Jiang, 2017; Dai et al., 2019). A sustainable approach to land management requires to avoid potential competition between bioenergy crops, which are rapidly increasing in Europe (≈ 13 % of agricultural land in 2013) and food production (European Commission, 2017). To this end, the use of agricultural and industrial waste biomass could be a favorable strategy for a sustainable development of the bioenergy sector (Conti et al., 2016; Aracil et al., 2018).

Indeed, wood and agricultural biomass waste play a significant role in the National Renewable Energy Action Plans (NREAPs) of the EU Member States and in their strategies to exploit bioenergy (Ardolino and Arena, 2019; Bais-Moleman et al., 2018).

The availability of waste biomass in EU Member States was recently assessed by Searle and Malins (2016) to be more than 445 million tonnes per year (dry basis), considering the contributions of agricultural (70%), forestry (16%) and other biomass waste such as food, animal, vegetal, sludge…(14%). For the U.S., the estimated total waste biomass is around 680 million dry tonnes (U.S. Department of Energy, 2011)".

A wide number of biomass conversion technologies can be used for biomass valorization: e.g. biochemical (enzymatic conversion, fermentation, anaerobic digestion), thermochemical (combustion, gasification, pyrolysis, hydrothermal liquefaction), and physicochemical (extraction and hydrolysis) (State et al., 2019; Adams et al., 2018; Sansaniwal et al., 2017; Zhang et al., 2017; Hornung, 2014; Tekin et al., 2014 Damartzis and Zabaniotou, 2011). Such consolidated conversion technologies and in particular pyrolysis, have been extensively studied (e.g. see Hu and Gholizadeh, 2019; Elkhalifa et al., 2019), also considering their environmental and economic aspects (Vázquez-Rowe et al., 2015; Patel et al., 2016; Paolotti et al., 2017; Joseph et al., 2010).

In the present study, the potential application of a novel process for biomass conversion, the Thermocatalytic Reforming (TCR) process, integrating pyrolysis to the catalytic reforming of its volatile products, was assessed from an environmental and techno-economic standpoint.

The TCR technology is an intermediate pyrolysis process with downstream post-reforming of the products (Neumann et al., 2015). The purpose of the process is to invest part of the energy of the original biomass waste to generate conversion products (namely syngas, bio-oil and bio-char) which, with the exclusion of Syngas, are characterized by a higher energy stored per unit volume [J/m$^3$] with respect to the starting biomass. The process produces a syngas which is rich in hydrogen, a bio-char suitable to be used as soil amendment or as an agent for soil remediation (Conti et al., 2017), and a stabilized bio-oil suitable for a further upgrade by hydrodeoxygenation processes (Neumann et al., 2016). The main advantage of this process with respect to the existing ones (Dai et al., 2019), is the possibility to convert a wide range of biomasses, including those characterized by high humidity and high contents of ash, obtaining three valuable product fractions (Conti et al., 2016). Furthermore, small to medium scale (2 to 30 kg/h of feed) mobile conversion systems based on TCR may be easily displaced and operated where the biomass is produced, with the aim of reducing the environmental and economic impacts of long distance transportation. Laboratory scale plants (2 kg/h of dry biomass feed) and pilot scale plants are currently available, and larger plants are under design (Jäger et al., 2016). The aim of this study is to assess the environmental and economic performances of such a promising technology when integrated to biomass waste to energy conversion processes representative of the European agricultural context, with the final goal of providing an approach to assess the sustainability of waste valorization options, alternative to disposal, based on advanced biomass conversion processes. To this aim, two biomass waste fractions were selected for the analysis: residues from olive wood pruning and digestate from anaerobic digestion. Olive wood pruning is an example of low-content moisture biomass, and is considered to be representative of woody residues produced from pruning of agricultural lands (Jäger et al., 2016). Digestate was selected as representative of high-moisture biomass, since its initial water content is usually around 90 wt% (Conti et al., 2016). A comparison with the use of raw digestate as soil amendment was carried out, being this a realistic alternative use of this waste biomass (Elkhalifa et al., 2019; European Commission, 2008), also considering its effectiveness and ecological function for the soil system. Environmental and economic sustainability indicators were used to assess alternative scenarios for the final use of the products obtained from the conversion of the two biomass waste fractions considered. The overall methodology allowed the identification of the alternatives showing the highest potential for the sustainable exploitation of the waste fractions, thus supporting a holistic approach to decision-making, addressing the environmental and economic sustainability since early process design.

## 2. METHODOLOGY

### 2.1 Description of the TCR biomass conversion process

The TCR consists of a pyrolysis stage (between 400 and 500 °C) and a reforming stage. During the reforming stage the syngas, bio-oil and char produced during the pyrolysis stage are maintained at temperatures between 500 and 700°C. Product yields and quality are sensitive to the composition of the feed, but typically 30-45% of the biomass is converted into syngas, 7-15% into bio-oil, 25-50% into bio-char. Water is produced as a by-product (15-25%). As mentioned above, in principle any type of biomass can be processed in the TCR, provided that the moisture content is up to 30 wt% and the biomass is pelletized up to 1 cm (Conti et al., 2016; Jäger et al., 2016). In the present study, a 30 kg/h potentiality was selected, since this is the ideal size of a TCR process for mobile applications.

The waste biomass conversion process is composed of the following steps: the raw biomass is dried to limit the water content to 30% before the conversion step, in which bio-char and volatile organic compounds are formed; the latter are then cracked to syngas and bio-oil in the reforming stage. Finally, the bio-oil and water are separated from syngas using a condensation process. A schematic representation is shown in Figure S1 of the Supplementary Material.

### 2.2 Feedstock supply and scenarios analysed

In order to correctly assess the economic and environmental impacts, a simplified system for the feedstock supply was defined for each biomass waste analysed. For the case of waste from olive tree pruning, the biomass feed is constituted of the product of olive trees pruning. In Italy, the average production of olive tree pruning is approximately 1.7 ton/ha per year (Cotana and Cavalaglio, 2008). Presently, in all the EU Countries where olive trees are farmed, such wastes are not valorised and are mostly burned on site in open air Thus, the possible energy valorisation is not competing with any alternative use of the biomass stock. The composition assumed for the waste biomass feedstock is derived from literature and reported in Table S1 of the Supplementary Material.

The feedstock supply system consists of the following main steps: collection and chipping of olive trees trimmings, transportation of the biomass to the conversion site, biomass conversion, product transportation, and final use (Figure 1a). The production of the biomass itself (agricultural operations, irrigation, materials for soil improvement and disease control, pruning) was excluded from the boundaries of the current analysis as it may be reasonably allocated completely to the olive and/or olive oil production lifecycle. However, the amount of $CO_2$ captured by photosynthesis during the growth of the pruned twigs and branches was accounted for in the environmental evaluations.

In the scenarios discussed below, several alternative off-site uses were considered for the product fractions obtained from TCR. The analysis of the impacts arising from these specific uses lays beyond the scope of the present study. Thus, when off-site use is considered, only the impact of transportation to a reference distance and the release of the carbon content due to the final conversion of the product fraction to $CO_2$ is accounted, since this is implicit in all envisaged uses (either in use for energy purposes or from end-of-life disposal of the goods produced from the TCR product fractions).

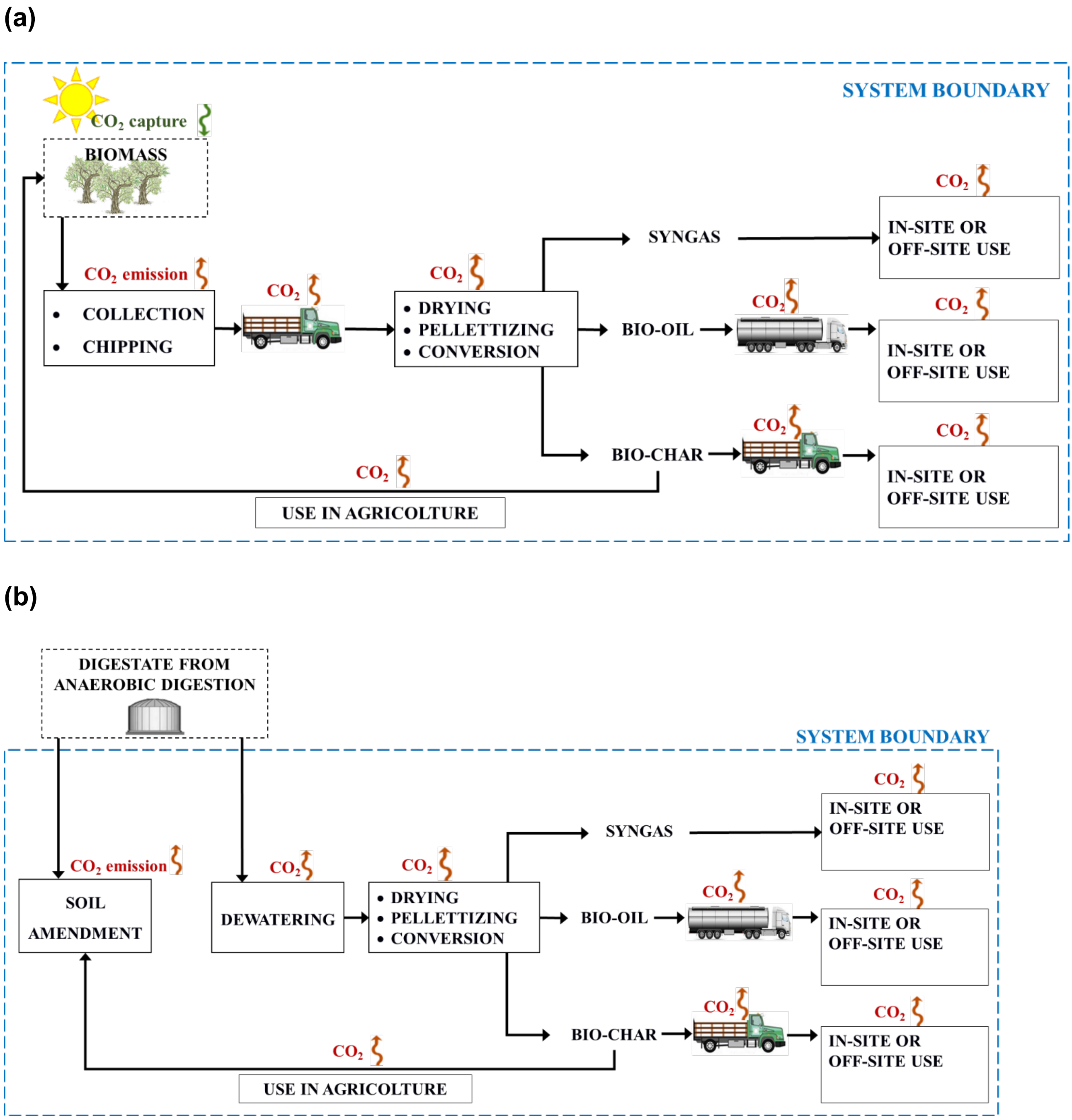

**Figure 1:** **Structure of the feedstock supply system considered for the valorisation of olive tree pruning (a) and digestate (b) waste fractions. The steps involved in $CO_2$ capture and emission are shown.**

Digestate is the residue of anaerobic digestion of biodegradable feedstock aimed at biogas production, and consists of dead microorganisms, indigestible material and water. The volume of digestate produced is approximately 90-95% of the feedstock to the anaerobic digestion process (Scarponi et al., 2016). Nowadays, the principal use of digestate is as a soil conditioner. Previous work proved the convenience of applying conversion technologies prior to digestate spreading on fields for fertilisation rather than directly spreading the raw product, due to the important reductions in air emissions of ammonia (Vázquez-Rowe et al., 2015). Indeed the main limitation to spreading raw digestate is the environmental issue posed by nutrient leaching and runoff into ground and surface waters (in particular nitrogen and phosphorus). For these reasons, the spreading of digestate to land is limited on the basis of its composition (Lukehurst et al., 2010). Such scenario was included in the analysis as a benchmark for the comparison of alternatives, whereas the impacts related to the anaerobic digestion process were entirely allocated to biogas production, which was not considered since it falls out the scope of the present analysis. In Table S1, the composition assumed for the digestate in the present study is reported.

The feedstock supply system analysed for the case of digestate has a structure similar to the one of waste from olive tree pruning, as shown in Figure 1b. Also in this case, the system boundary excludes the production of the waste biomass. Given the higher complexity of the processes excluded (several unit operations, mix of feedstocks in biogas production), the capture of $CO_2$ by photosynthesis in the biomass growth processes is not considered in this case (i.e. is assumed as out of the system boundary). The digestate conversion process (dewatering, drying, pelletizing, thermochemical conversion) is supposed to occur at the same site where the digestate is produced (anaerobic digestion process for bio-gas production). Actually, the transportation of digestate with a high water content (≈ 90 wt %) is not a realistic scenario from the economic standpoint. A dewatering stage using a belt filter press was also considered, to reduce the water content of digestate from 90%wt to 60%wt (Pradel et al., 2013). The TCR biomass conversion process requires an energy input in terms of both thermal and electrical energy. Energy self-sustainability of the biomass conversion process is thus a key issue in sustainability analyses. The use of some of the conversion products for the energy self-sustainability of the TCR itself potentially leads to economic and environmental advantages, as it avoids or limits the need to purchase energy produced from fossil fuels.

Table 1 reports a qualitative description of the alternative scenarios considered in the techno-economic and environmental analysis of the TCR conversion process of the two waste fractions. The scenarios were obtained based on a preliminary analysis of potential end-uses of the product fractions obtained by the TCR (Neumann et al., 2016). A base-case was defined, where the conversion products are transported off-site for energy production and the energy requirements of the process, in terms of electrical and thermal power, are satisfied using the national power and gas grids (Baseline Scenario). Scenario 1 is similar to Baseline Scenario, the only difference being the use of bio-char for soil amendment rather than for energy production. In all the other scenarios (Scenarios 2 to 5) the energy self-sustainability of the TCR process is achieved using different energy mixes, including the product fractions obtained from TCR conversion. More in detail, the in-site energy use of the conversion products explored different techniques: (i) the production of thermal energy from direct combustion (suitable for every product), and (ii) the combined heat and power (CHP) generation (for the syngas only). Off-site use of the conversion products were also explored: (i) the use of the bio-char in agriculture as soil amendment, and (ii) other uses of the products. A specific remark applies to Scenario 2, where a difference is present for the two biomass wastes considered: in the case of waste from olive tree pruning, the use of both syngas and bio-oil is necessary to comply with the energy demand of the TCR process, whereas for the case of digestate the conversion of bio-oil is sufficient to satisfy the energy requirements of the conversion process, so that syngas can be sold for energy use.

Clearly enough, the alternative scenarios for the final use of the products will affect the carbon foot print and the economics of the system. For instance, in Scenario 1, bio-char is sold and transported to field as soil amendment, whereas syngas and bio-oil are used off-site for energy production: this solution improves environmental sustainability with respect to Baseline Scenario (where bio-char is used to produce energy) due to bio-char carbon sequestration characteristics (Bamdad et al., 2018; Madzaki et al., 2016).

**Table 1: Description of the alternative scenarios defined for the use of the product fractions obtained from the TCR conversion.**

| SCENARIOS | DESCRIPTION |
|---|---|
| **Baseline Scenario** | All the conversion products transported off-site for energy production. |
| **Scenario 1** | Syngas available for off-site energy production.<br>Bio-oil transported off-site for energy production.<br>Bio-char transported to fields as soil amendment. |
| **Scenario 2** | Bio-char transported to fields as soil amendment.<br>Bio-oil available for in-site energy production.<br>Syngas available for in-site energy production (in the case of olive pruning) or Syngas available for off-site energy production (in the case of digestate). |
| **Scenario 3** | Syngas available for in-site energy production.<br>Bio-oil transported off-site for energy production.<br>Bio-char transported to fields as soil amendment. |
| **Scenario 4** | Bio-char available for in-site energy production.<br>Syngas available for off-site energy production.<br>Bio-oil transported off-site for energy production. |

| | |
|---|---|
| **Scenario 5** | Syngas available for in-site combined heat and power generation (CHP).<br>Bio-oil transported off-site for energy production.<br>Bio-char transported to fields as soil amendment. |

## 2.3 Procedure for the calculation of performance indicators

In each scenario, the inputs and outputs of the conversion process and of the feedstock supply were quantified in order to allow for the calculation of performance indicators. This step is conceptually similar to the definition of the lifecycle inventory in a LCA study. A reference potentiality for the conversion process was assumed as 30 kg/h of processed dry biomass, representative of a medium scale TCR unit. A total of 8280 yearly hours of operation were considered to assess the yearly potentialities of the systems.

The inputs and outputs of the conversion process were evaluated on the basis of mass and energy balances. The mass balance for the conversion process was solved on the basis of the experimental results in terms of product yields available in the literature. In particular, the study of Jäger et al. (2016) was assumed as a reference for the case of waste from olive tree pruning, and that of Conti et al. (2016) for digestate.

The energy balance was solved to calculate the power to be supplied (or removed) by (from) the system, being the specific enthalpies known for all the streams at given process conditions (temperature and pressure). When analysing the in-site energy production needed to meet the demand of the conversion process and related pre-treatments, the recovery of thermal energy from the combustion of the TCR products using different technologies was explored. A simple combustor (thermal efficiency, $\eta$th,c, 100%) and a CHP unit for the sole case of syngas ($\eta$th,CHP = 52%, Scarponi et al., 2016) were considered as possible alternatives. The overall thermal efficiency of the recovery process ($\eta$th,O) was calculated for such alternatives as the thermal efficiency of the combustion technology ($\eta$th,T) deducted of the ratio between the energy recoverable from combustion of the product and available at the required temperature (i.e. the operating temperature of the conversion process or pre-treatments) and the potential energy of the product (E0):

$$\eta_{th,O} = 1 - \eta_{th,T} - \frac{\dot{m}_{exhaust} \cdot c_{Pexhaust} \cdot (T_{operating} - T_{amb})}{E_0} \qquad \text{Eq. (1)}$$

where $E_0$[W] is defined as the product between the mass flow rate of the stream and its higher heating value. In Eq. (1), $\dot{m}_{exahust}$ [kg/s] and $C_{Pexahust}$ [J/kg·K] are the mass flow rate and the heat capacity of the exhaust gas generated from the combustion of the TCR products, whereas the temperatures are expressed in K. Ambient temperature, $T_{amb}$ was considered equal to 25°C. For the scenarios entailing the off-site use for energy of the TCR products, the use of a simple combustor was assumed.

When off-site use of conversion products was examined, transportation was accounted for, using reference distances based on the scale of the TCR considered, which targets SMEs in the European context. Transportation distances of 50 km by 7t lorry were assumed for bio-char when used for soil amendment, whereas a transportation distance of 200 km (7t lorry) was assumed for off-site use of any product fraction.

## 2.4 Environmental and economic performance indicators

Currently, one of the most critical environmental concerns identified for energy systems is the contribution to global warming derived from the emission of greenhouse gases (GHGs) (Bruckner et al., 2014). This aspect is of paramount importance when comparing alternative energy production scenarios based on biomass waste, as the raw material itself is both renewable and a waste, making impact categories related to resource depletion and competitive use of land less critical in the study. On the other hand, evaluation of environment impacts different than GHG is generally difficult at the current level of detail of the supply system considered (e.g. fugitive emissions of the scaled up TCR process are not known). For this reason, the environmental performances of the different scenarios were evaluated by calculating an indicator for greenhouse gases emission. It should be noted that the fossil GHG indicators, also allows some insight on other environmental issues (e.g. resource depletion, acidification), as they are all roughly proportional to the energy demand of the system (Huijbregts et al., 2010; Steinmann et al. 2016).

The approach based on the global warming potential (GWP), where GHG emissions are quantified in terms of kilograms of $CO_2$ equivalents, was adopted (IPCC, 1991). This approach allows also defining the incidence of each step (j) on the on the overall performance of a specific scenario (k) of the system (Paolucci et al., 2016; Uusitalo et al., 2014), according to the following equation:

$$\mathbf{GHG_{tot,j} = GHG_{fossil,j} + GHG_{biogenic,j} = \sum_{i=1}^{n} f_{fossil} \cdot F_i + \sum_{b=1}^{m} f_{biogenic} \cdot F_b} \quad \text{Eq. (2)}$$

The approach also allows checking if the overall GHG balance (Eq. 3) is positive or not for the scenario analyzed

$$\mathbf{GHG_{tot,k} = \sum_{k=1}^{k=j} GHG_{tot,j}} \quad \text{Eq. (3)}$$

As per Eq. 2, the GHG emissions of each step are calculated as the product of an emission factor, f, representing the $CO_2$ equivalents emitted per unit product, and the quantity of unit product, F, present in each step. Particular care was dedicated to account the flows of biogenic and fossil $CO_2$ separately. Biogenic $CO_2$ emissions are those directly resulting from the combustion or decomposition of biologically-based materials other than fossil fuels (EPA Science Advisory Board (SAB), 2011). Similarly, the photosynthesis process, capturing atmospheric $CO_2$ in biologically-based materials, is considered here a sink of biogenic $CO_2$. The $CO_2$ emissions indicator was calculated based on one year of activity. The $CO_2$ emission factors used for its calculation are reported in Table S2 and Table S3 of the Supplementary Material, and were obtained from the European reference Life Cycle Database (European Joint Research Center, 2016) and ECOINVENT Database version 3.3 (Centre for Life Cycle Inventories, 2016).

The Net Present Value (NPV) was selected as the economic indicator for the analysis of each scenario. The NPV allows to define the value generated by an initiative, so from an economic standpoint the objective is to maximize the NPV. The NPV consist in the sum of all discounted cash-flows associated with the conversion process and feedstock supply system (investments, raw material and energy costs, revenues from sale of conversion products, etc.) as in the following equation:

$$NPV = \sum_{k=1}^{n} \frac{F_k}{(1+r)^k} - I \qquad \text{Eq. (4)}$$

where $F_k$ is the cash flow generated by the overall process each year, I is the initial investment for year k = 0, r is the discount rate, that was assumed to be 8% (a typical average value for new energy installations, Carlini et al., 2017; Karellas et al., 2010), and n is the time horizon considered, assumed to be 10 years. The Internal Rate of Return (IRR) was also calculated, being the value of the discount rate (*r* in Equation 4) that makes the NPV equal to zero, and it is typically used to estimate the profitability of a potential investment: the higher the IRR, the more attractive the investment is. In other words, the IRR is the lowest value of *r* that justifies the investment.

The investment costs were associated to the equipment included in each system analysed. The cost of each piece of equipment was estimated starting from data available from suppliers and from the literature.The price of specific equipment such as the TCR, the CHP unit, and the biomass pelletizing machine were obtained from vendors, and refer to year 2017. In the case of the TCR unit, the cost was scaled-up based on the commercial price of a 2 kg/h unit, using an exponential method with exponent 0.6 (Don W. and Robert H., 2007). The price of the other general purpose equipment items, such as the biomass dryer and the belt filter press, was estimated from the literature (Don W. and Robert H., 1999) and converted to year 2017 by suitable cost indices. Details are reported in the Supplementary Material (Tables S6 and S7).

The operating costs and the revenues were considered constant per every year of the time of the investment. The operating costs considered are summarized in Table S7, and the revenues considered from the sale of products are reported in Table S8. Since the sale price of such emerging products are subject to uncertainties and market fluctuations, a sensitivity analysis of the NPV was carried out.

# 3. RESULTS AND DISCUSSION

## 3.1 Analysis of the TCR conversion process

The results obtained for the mass and energy balance considering 30 kg/h of dry biomass converted, are reported in Table 2, while Table 3 reports the thermal energy requirements for the process. The potential energy of the different product fractions was calculated in order to track the partitioning of the energy content. The results in Table 2 show that the energy is conveyed mainly to syngas and bio-char for both feedstock samples.

**Table 2: Results of the mass and energy balance for the TCR conversion of the waste biomass samples considered.**

**WASTE FROM OLIVE TREE PRUNING**

| Properties of the stream | Biomass Dry | Bio-char | Bio-Oil | Water | Syngas |
|---|---|---|---|---|---|
| **Higher Heating Value, HHV [MJ/kg] (Jäger et al., 2016)** | 19.2 | 30.3 | 33.6 | 6.2 | 14.8 |
| **Temperature, T [°C]** | 126 | 700 | 10 | 10 | 10 |
| **Mass flow rate, M [kg/h]** | 30 | 6.0 | 1.2 | 5.1 | 17.6 |
| **Potential energy, $E_0$ [kW]= M·HHV** | 160 | 50.5 | 11.1 | - | 72.0 |

**DIGESTATE**

| Properties of the stream | Biomass Dry | Bio-char | Bio-Oil | Water | Syngas |
|---|---|---|---|---|---|
| **Higher Heating Value, HHV [MJ/kg] (Conti et al., 2016)** | 16.9 | 17.5 | 35.6 | 3.1 | 11.2 |
| **Temperature, T [°C]** | 126 | 700 | 10 | 10 | 10 |
| **Mass flow rate, M [kg/h]** | 30 | 11.8 | 1.7 | 6.8 | 9.4 |
| **Potential energy, $E_0$ [kW]= M·HHV** | 140 | 57.4 | 16.7 | - | 29.4 |

**Table 3: Thermal energy required by the system for the waste biomass samples considered.**

**WASTE FROM OLIVE TREE PRUNING**

| EQUIPMENT | Operating temperature [°C] | Thermal Power [kW] | Electrical Power [kW] |
|---|---|---|---|
| **Dryer** | 126 | (-) 16.5 kW | - |
| **Pelletizer** | - | - | (-) 11 kW |

| | | | |
|---|---|---|---|
| **TCR** | 400-700 | (-) 33 kW | - |
| **Condensing Unit** | 10 | (+) 3.8 kW | - |
| | **DIGESTATE** | | |
| **Dryer** | 266 | (-) 50.3 kW | - |
| **Pelletizer** | - | - | (-) 11 kW |
| **TCR** | 400-700 | (-) 62.8 kW | - |
| **Condensing Unit** | 10 | (+) 3.7 kW | - |

***(-) to be supplied to the system; (+) to be removed from the system.***

For both cases, the energy balances were then applied to the calculation of the energy requirements (or production) of each of the alternative scenarios considered. The results are reported in Table 4. As mentioned above, excluding Scenarios 0 and 1 in which external energy supply was assumed, the other scenarios were designed to achieve the energy-self sustainability of the TCR conversion process by means of the production of thermal power (HG) via combustion of the products, as well as the combined heat and power generation for the case of the syngas (HG + EG).

As shown in Table 4, for all the scenarios analysed, an integration of thermal power (using methane from the national gas grid) was necessary in order to meet the energy requirements posed by the drying process used as a pre-treatment for the biomass (as shown in Table 2 and Table 3).

Furthermore, for all those scenarios in which the simple combustion of the products was assumed (i.e. 2 to 4), the use of electric power required by the biomass pelletizing step was covered by the national grid. In Scenario 5, where a CHP unit was integrated in the system, a more complex situation is present. In the case of waste from olive tree pruning, the use of syngas in a CHP unit was enough to cover the electric power requirement, whereas for the case of digestate an integration from the national electric grid was needed. This is due to the different quantity and quality (Higher Heating Value) of syngas produced from the TCR conversion in the two cases (see Table 2 and Table 3).

**Table 4: Results of energy balances for each of the alternative scenarios considered (the allocation of each product fraction in each scenario is also reported).**

| | Baseline Scenario | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|---|---|---|---|---|---|---|
| **SYNGAS** | EU (100%) | EU (100%) | HG (100%) | HG (100%) | EU (100%) | HG+EG (100%) |
| **BIO-OIL** | EU (100%) | EU (100%) | HG (100%) | EU (100%) | EU (100%) | EU (100%) |
| **CHAR** | EU (100%) | TL (100%) | TL (100%) | TL (100%) | HG (100%) | TL (100%) |
| | | | **WASTE FROM OLIVE TREE PRUNING** | | | |
| **Electric Power [kW]** | (-) 11 | (-) 11 | (-) 11 | (-) 11 | (-) 11 | (+12) |
| **Thermal Power [kW]** | (-) 53.5 | (-) 53.5 | (-) 8.5 | (-) 15.5 | (-) 27.5 | (-) 18 |
| | | | **DIGESTATE** | | | |
| **Electric Power [kW]** | (-) 11 | (-) 11 | (-) 11 | (-) 11 | (-) 11 | (-) 1.6 |
| **Thermal Power [kW]** | (-) 116.8 | (-) 116.8 | (-) 107.8 | (-) 98.1 | (-) 81.8 | (-) 104 |

***EU: External Use; HG: Heat generation; EG: Electricity generation; TL: To Land.***

***(-) power from the national grid; (+) power to the national grid.***

## 3.2 Environmental indicators

Figure 2 shows the contribution of each step of the system to biogenic and fossil $CO_2$ emissions, respectively for the olive (panel a) and digestate (panel b) conversion. In Table S2 and S3 of the Supplementary Material the corresponding numeric values are listed.

In the analysis of the olive tree pruning waste feedstock supply conversion, collection and chipping were associated to all the scenarios considered, thus the same impacts were included for the transportation and pelletization of the biomass wastes. The off-site use of all product fractions for energy production via combustion (Baseline Scenario) resulted the less environmentally sustainable scenario. The use of char as soil amendment (Scenario 1) has a very positive effect on the total carbon footprint of the system, which becomes negative, as shown in Figure 2a. Indeed, all the scenarios in which this final use was assumed for biochar (all but Scenario 4) result in a negative carbon footprint. The lower values of the GHG indicator are obtained for Scenario 5: using the syngas in-site in a CHP unit allows to produce a surplus of electricity with respect to that required by the process, avoiding the fossil $CO_2$ emissions associated to the use of electric power from the national grid. A further positive effect of the in-site use of products is avoiding the emissions associated to transportation.

With respect to traditional scenarios (Morris, 2017), such as the in-site combustion of pruning olive trees trimmings or their landfill disposal, the valorization of the biomass via the TCR process thus has positive environmental outcomes.

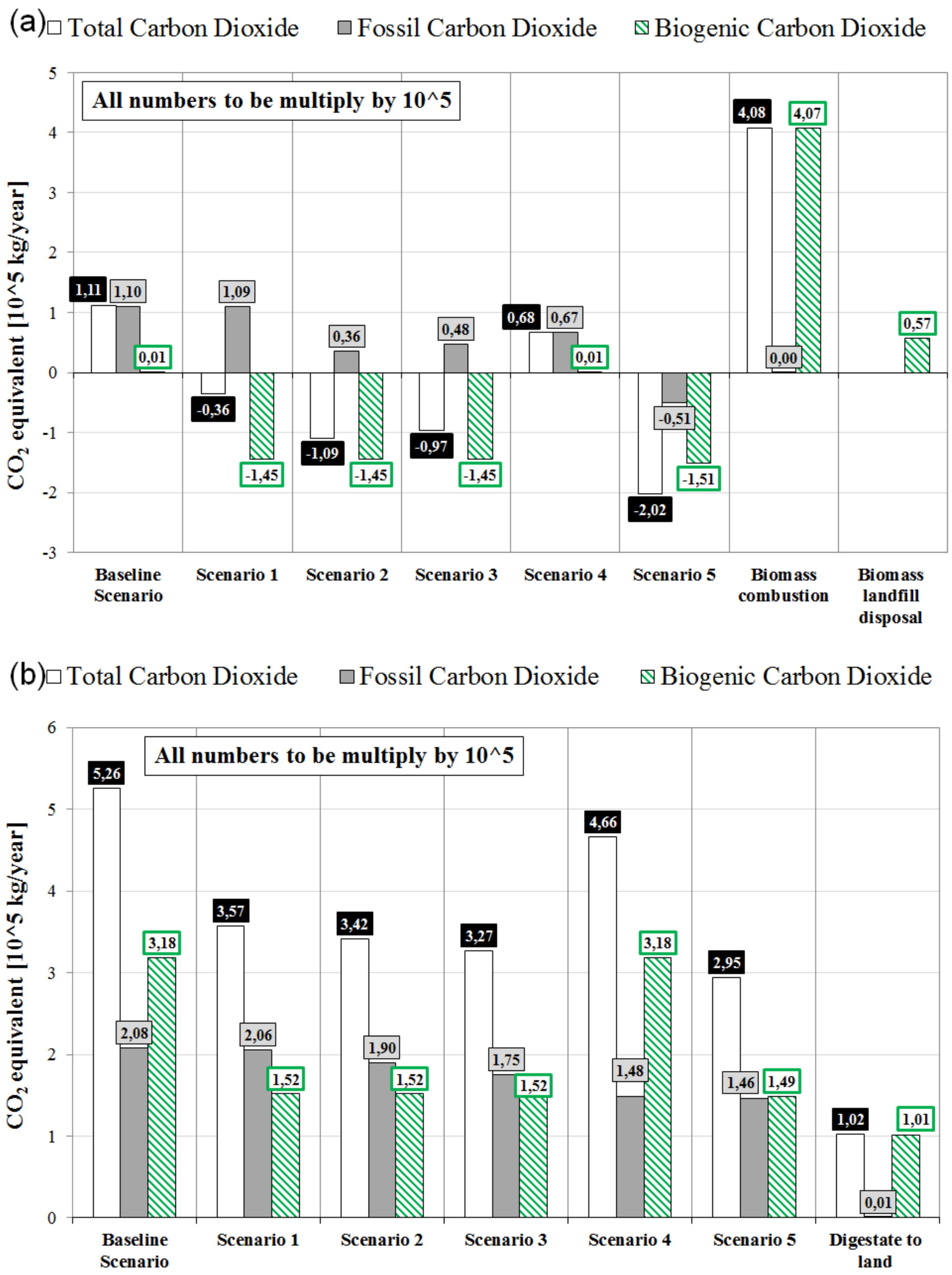

**Figure 2:** **Fossil, biogenic, and total $CO_2$ emission for the alternative scenarios considered for olive tree pruning (panel a) and digestate (panel b) conversion.**

When considering the digestate waste, it should be remarked that all the scenarios have the same carbon footprint for all the stages of the biomass pre-treatment, e.g. dewatering, pelletizing, and drying. It should be remarked that a higher temperature is thus required to dry the digestate (266 °C vs. 126°C), thus a higher energy requirement is present. The decision to exclude from the feedstock supply and conversion process boundaries the $CO_2$ capture during biomass growth results in a positive value of the environmental indicator for all the alternatives. It should be remarked that, similarly to the olive tree pruning case, this does not affect the comparison of the alternatives. Actually, the amount and composition of the processed digestate is the same for all the alternatives, and the contribution of $CO_2$ fixation by photosynthesis during biomass growth is therefore the same for all scenarios.

Similarly to the previous case, the scenario showing the lowest GHG emission indicator is Scenario 5, where the syngas produced is burned in-site in the CHP unit: the production of electricity avoids the $CO_2$ emissions related to the use of electricity from the national grid. Scenario 3 is very similar to Scenario 5, but it is penalized by the use of a standard combustor, that results in requiring the use of electricity from the national grid. Furthermore, the use of the products offsite entails impacts related to transportation.

### 3.3 Economic indicators

The results obtained for the values of the economic indicator calculated for all the alternative scenarios considered for the two feedstock supply and conversion processes analysed are reported in Table 5.

In the case of the waste from olive tree pruning, no scenario showed a positive NPV over a 10 years period. Provided that the investment cost is approximately 700k€ (85% due to the cost of the TCR unit), the best economic performances are obtained in Scenario 5, where investing in a CHP unit (≈ 50k€, 7% of the total investment) generates a positive cash flow associated to the revenues for the sale of the electricity produced exceeding operative costs, which benefit of the renewable energy incentives policies (KPMG International, 2015). The main contribution to the operating cost of the conversion process is imputable to maintenance (55% of the total operating costs). The external energy supply (natural gas and electricity) contributes for about the 20% of the operating costs, whereas the cost of the personnel counts up to 15%.

**Table 5: Economic assessment of the alternative scenarios analysed. .**

| | **Baseline Scenario** | **Scenario 1** | **Scenario 2** | **Scenario 3** | **Scenario 4** | **Scenario 5** |
|---|---|---|---|---|---|---|
| **WASTE FROM OLIVE TREE PRUNING** | | | | | | |
| **Operating costs [k€/y]** | 94 | 93 | 61 | 67 | 71 | 72 |
| **Revenues [k€/y]** | 41 | 41 | 25 | 41 | 16 | 94 |
| **Cash Flows [k€/y]** | -53 | -52 | -36 | -26 | -55 | 22 |
| **NPV [k€]** | -1010 | -1005 | -900 | -830 | -1030 | -550 |
| **IRR [%]** | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 | - 16 |
| **DIGESTATE** | | | | | | |
| **Operating costs [k€/y]** | 133 | 132 | 126 | 120 | 108 | 127 |
| **Revenues [k€/y]** | 73 | 73 | 49 | 73 | 24 | 94 |
| **Cash Flows [k€/y]** | -60 | -59 | -77 | -47 | -84 | -33 |
| **NPV [k€]** | -1072 | -1067 | -1185 | -980 | -1235 | -880 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **IRR [%]** | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 | Cash flow < 0 |

Clearly enough, IRR was calculated for scenarios with positive cash flows, i. e. Scenario 5 of the waste from olive tree pruning case (see Table 5). The result is a negative value (≈ -16 %), meaning that the sum of cash flows is less than the initial investment (≈ 700 k€ including the CHP unit, see Table S5 in the Supplementary Material). Therefore the negative NPV will be obtained, at the given prices and time horizon, no matter the discount rate considered. In the case of Scenario 5, a sensitivity analysis was carried out in order to explore the effect on the NPV of the sale price of the conversion products. Presently no established market exists for the product fractions obtained from TCR conversion. Thus, the market price is subject to large uncertainties (Jirka, 2013; Jirka and Tomlinson, 2014; Italian Regulatory Authority for Energy, 2013). Based on available data, reasonable ranges of variation were defined for two key products:

- bio-oil: 0 to 25000 €/ton (Italian Regulatory Authority for Energy, 2013);
- bio-char used as soil amendment: 250-2000 €/ton (Jirka, 2013; Jirka and Tomlinson, 2014).

The income from selling the electricity surplus produced by the CHP was kept constant (0.28€/kWh) as for biogas installations. Figure S2-a shows the results obtained for NPV as a function of the market prices of bio-oil and bio-char. It can be observed that positive values of NPV may be obtained for reasonable values of the selling prices of bio-oil and bio-char when including a CHP unit to convert in-site the produced syngas. This result is in agreement with those recently obtained by previous authors (Aui et al., 2019; Cambero et al., 2016). It is worth noticing that the main economic advantage of using TCR is the production of a valuable biochar, that may be sold and the market at higher prices than conventional fertilizers (250-400 ∈/tons, https://www.cso.ie/multiquicktables/quickTables.aspx?id=ajm05).

Also in the case of digestate, no scenario showed a positive value of NPV based on the economic parameters assumed, as evidenced by the results reported in Table 5. In relative terms, the best scenario is again that including the use of a CHP unit (Scenario 5), that benefits of revenues from selling the surplus of electricity produced by the syngas at a favourable price. A sensitivity analysis of the NPV of Scenario 5 was performed, using the same procedure applied in the case of olive waste conversion. The results are reported in Figure S3-b. Also in this case, varying the prices of the TCR product fractions within a credible range allows obtaining a short payback period of the investment and generates a revenue higher than the invested capital.

Similarly, the IRRs have been calculated, varying the prices of bio-oil and char as forehead mentioned. The results are reported in Tables S9 an S10. For the case of waste from olive tree pruning, typical values of the discount rate (Carlini et al., 2017; Karellas et al., 2010) are obtained when the prices are in the range 5 k€/ton for bio-oil and 1 k€/ton for bio-char, or 10 k€/ton for bio-oil and 0.5 k€/ton for bio-char. Lower values implies negative IRRs. For the case of digestate, typical values of the discount rate (Carlini et al., 2017; Karellas et al., 2010) are possible for higher prices of the products, i.e. in the range 5 k€/ton for bio-oil and 1.5 k€/ton for bio-char or 10 k€/ton for bio-oil and 0.75 k€/ton for bio-char. Hence, unless a reduction of operating costs (e.g. cost of maintenance and cost of energy) is possible, economical convenience occurs only for relatively high values of the prices of the products.

### 3.4 Analysis of the environmental and economic indicators for the alternative scenarios

For the sake of a direct comparison of the overall environmental performances, the total $CO_2$ emissions calculated for each scenario were normalized with respect to the worst-case scenario obtained for each conversion system (i.e. Baseline Scenario). The results are reported in the radar plot shown in Figure 3-a. Data labels represent the % variation with respect to worst-case scenario. As mentioned above, for both biomass wastes, it is possible to appreciate the environmental benefits of self-producing the energy required for the conversion process on-site using the syngas via CHP generation (Scenario 5).

The comparison between the two panels highlights the importance of the characteristics of the waste biomass to be converted: in the case of olive tree pruning waste, the initial potential energy of the biomass ($E_0$ in Table 2) is higher with respect to the digestate. Furthermore, in this case, the TCR conversion process allows transferring most of the initial potential energy to the syngas, which has a greater value of the Higher Heating Value (see Table 2) and is obtained in higher amounts than in the case of digestate.

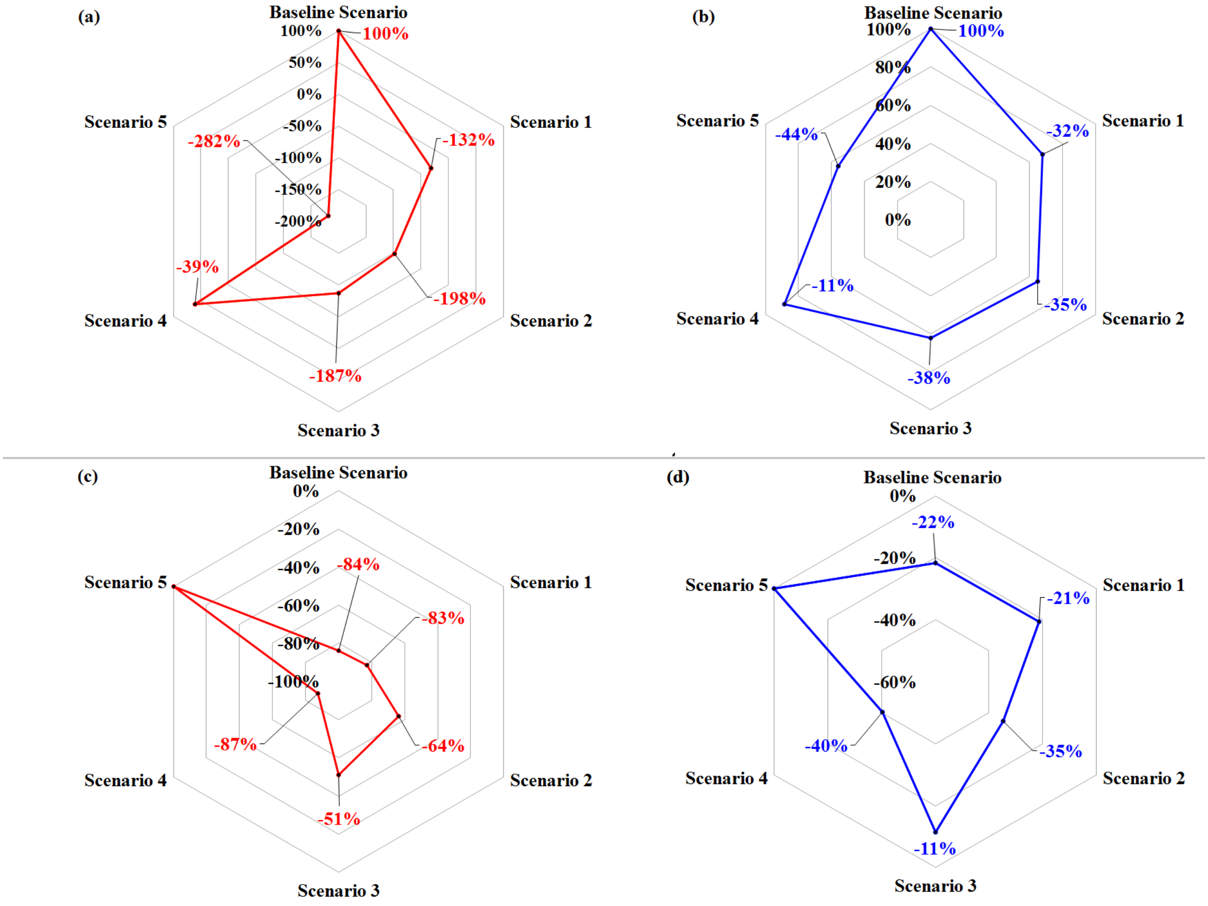

**Figure 3: Radar plot of the normalized total $CO_2$ emissions associated to each scenario of the olive waste (a) and the digestate waste conversion (b). Data labels show the % variation with respect to worst-case scenario. Radar plot of the normalized NPV associated to each scenario of the olive waste conversion (c) and digestate waste conversion (d). Data labels show % economic losses with respect to the best-case scenario.**

A similar approach was adopted for the comparison of the economic indicators with the aim of revealing the worse options for the use of products, which is a key-issue during the design stage. In this case, the NPVs were normalized with respect to the best-case scenario obtained for each conversion process (i.e. Scenario 5). The results are reported in the radar plot shown in Figure 3 panel c and d. Data labels represent the % variation (i.e. economic losses) with respect to the best-case scenario.

Scenario 3 was found to be the second best option. Indeed it is very similar to Scenario 5: the only difference lays in the fact that syngas is used for heat generation only in Scenario 3, whereas it is used for heat and electrical power generation in Scenario 5. Therefore, with respect to Scenario 5, Scenario 3 implies a higher amount of $CO_2$ emissions due to the use of the national power grid for electricity supply, leading to economic implications.

As a general result, the Figure shows that the worst-case scenario is Scenario 4, where a valuable product, such as bio-char, is used for energy production and is not delivered to the market: the price of biochar is higher than the price of the energy produced by its combustion. This is why all the scenarios in which biochar is sold as soil amendment shows best economic performances. Moreover, in Scenario 4, all the required energy is purchased from the national grid.

The benefits of self-producing energy, in particular thermal energy, are evident when comparing the results obtained for Scenario 2: in the case of digestate, the thermal power required by the TCR process was obtained by bio-oil combustion, whereas the thermal power required by biomass drying was obtained from combustion of gas from the national gas grid. This resulted in a negative outcome from an economic standpoint, being the natural gas the highest operating cost of the entire feedstock supply and conversion process.

## 4. CONCLUSIONS

The environmental and economic sustainability of a novel process for biomass waste valorisation based on TCR conversion, was assessed. An approach based on the calculation of environmental and economic indexes was developed to analyse the alternative scenarios defined for the final use of the products obtained from biomass waste conversion.

The results evidenced that, for a medium size facility integrated in a realistic agricultural context, the overall performances of the TCR are strongly related to the characteristics of the biomass to be converted, that influence both the severity of the required pre-treatments as well as the quality of the products obtained.

In accordance with previous findings (Blengini et al., 2011), sustainability of biomass waste valorisation processes is not straightforward to obtain. The calculated values of environmental and economic indexes point out criticalities even when compared to waste disposal with no energy or material recovery.

However, a key advantage of TCR is the production of a high quality bio-char that may be used for soil amendment. Since the use of bio-char results in evident environmental benefits evidenced by the environmental and economic indexes defined, this is a key advantage for the sustainability of the TCR process among alternatives.

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