Exploring the production of bio-energy from wood biomass. Italian case study

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Abstract

The concerns related to the environmental impact related to energy production from fossil fuel are increasing. In this context, the substitution of fossil fuel based energy by bio-energy can be an effective solution. In this study, the production of electricity and heat in Italy in a combined heat and power plant (CHP) based on an Organic Rankine Cycle (ORC) turbine from wood based biomass both from forest and agricultural activities has been analysed considering four potential alternative scenarios to the current energy status: biomass from very short rotation forestry (VSRF) poplar and willow stands as well as residues from natural forests and from traditional poplar plantations. The evaluation has been performed by applying Life Cycle Assessment (LCA) method and an attributional cradle-to-gate approach has been followed. The expected savings of greenhouse gases emission and fossil fuels demand have been quantified, as well as derived emissions of toxic pollutants and substances responsible for acidification, eutrophication and photochemical oxidant formation.The results have been also compared with the conventional Italian scenario considering the current Italian electricity profile and heat production from natural gas. Among the different scenarios, due to the lower transport distance, the use of biomass from traditional poplar plantation residues shows the lowest impact. The biomass combustion emissions are the main hotspot for several evaluated impact categories (e.g., particulate matter formation, human toxicity). In fact, when the produced bio-energy is compared to the reference system (i.e., electricity produced under the Italian electric profile) the results do not favor bio-energy systems. The results reported in this study support the idea that forest residues would be an interesting and potential feedstock for bio-energy purposes although further research is required specifically with the aim of optimizing biomass supply distances.

Keywords: CHP; Environmental sustainability; Forest residues; Life Cycle Assessment-LCA; Poplar; Willow

1. Introduction

Mitigation of climate change and derived effects is a global challenge (IPCC, 2007) motivating the international community to introduce easing strategies (Oreggioni et al., 2017). Therefore, European Union's energy and climate change plans try to avoid the use of fossil-based energy by means of the promotion of bio-energy (Directive 2009/28/EC; European Commission, 2018). In this sense, energy industries have contributed to ~32% of global CO_2 emission over the last 20 years (Janssens-Maenhout et al., 2012; Oreggioni et al., 2017) as well as heating and cooling processes are responsible for approximately 50% of the final European energy demand (Tsupari et al., 2017). Finally it is important to note that, in Europe, fuel combustion in energy industries is the most important contributor to anthropogenic climate change, with 28.5% of total greenhouse gases (GHG) emissions in 2015 (Eurostat, 2018).

Bio-energy is a critical issue for multiple reasons besides environmental concerns such as i) to guarantee energy security through a more diversified energy mix and less reliance on imported fossil-energy carriers, ii) the sustainable use of natural resources as well as iii) the need to revitalize rural economies (Buonocore et al., 2012; Börjesson Hagberg et al., 2016). Thus, an increased share of renewable energy is mandatory in energy system to satisfy the mentioned issues besides reducing greenhouse gases (GHG) emission. In addition, improvements in power plant efficiency and the incorporation of carbon capture and storage (CCS) processes are also required, receiving the latter special attention in recent years (Tsupari et al., 2017).

Bio-energy systems include a full range of products such as bio-ethanol, bio-diesel, biogas, electricity and heat, all of them from a large range of potential feedstocks – e.g., wood from forests, crops, seaweed and animal, forest and agricultural wastes (González-García et al., 2014). Moreover, biomass as its primary product is a versatile energy source that can be stored and converted to energy on-demand (De Meyer et al., 2014). The waste-to-energy concept is being highly promoted as a part of the efforts into sustainable development in energy sector (Ferreira et al., 2017). The use of forest and agricultural residues as well as other biomass waste from agricultural and industrial activities for bio-energy production (mainly electricity and heat) plays a key role in the energy system (Eurostat, 2015) and it is expected to increase over the next few years. According to the MISE (2012), the share of energy from renewable energy sources should reaches in 2020 the 17% of the national energy consumption. In this sense, there is a clear potential for increased use of wood for energy puposes in the EU, mostly related to forest residues and complementary fellings (SFC-WGII, 2008).

However, discrepancies also exist regarding bio-energy supply from biomass mostly due to the high cost associated to the production of biomass-based electricity (Cleary and Caspersen, 2015b). Therefore, to beat this economic barrier, many governments offer subsidies to encourage investment in bio-energy technologies. Bio-energy production costs, outside of the cost of feedstock production, tend to decrease with scale (Cameron et al., 2007; Dornburg and Faaij, 2001). Thus, supply-side funding programs frequently provide greater economic support for smaller-scale projects within a given technology class. However, the discontinuous availability and the relatively high maintenance and logistic costs hinder the economic convenience of biomass for large scale energy production (De Meyer et al., 2014). Therefore, numerous efforts are being carried out to make the whole process achievable from an economic approach (De Meyer et al., 2014)

Production of heat and electricity from woody residues either from forest or agricultural activities could considerably increase the contribution to energy security, reduce GHG emission and add value to waste materials (Matsumura et al., 2005; Fernandes and Costa, 2010; Aldana et al., 2014). Indeed, it is a common practice in factories such as pulp mills where pulp is generated together with heat and electricity (Sandin et al., 2015). Different studies evaluated the potential quantities of available forest biomass residues for energy production in countries such as Portugal (Fernandes and Costa, 2010; Viana et al., 2010; Lourinho and Brito, 2015) or Uganda (Okello et al., 2013). According to them, only if cogeneration is implemented the wood fuel resource should be sufficient to satisfay the required capacity demand. However, special attention must be paid into the biomass-supply competition with pellets production, one of the largest internationally traded solid biomass commodities for energy purposes mainly derived from wood residues (Sikkema et al., 2011; Monteiro et al., 2012).

Italy's energy profile relies to a very large extent on imports to meet its energy needs since Italian energy reserves are scarce. In this sense, Italy is a net importer of electricity and only 88.2% of demand is satisfied by a national production. Regarding its power production capacity, 15.3%

corresponds to hydropower and 15.9% derives from renewable sources, and the remaining is produced from fossil sources (Terna, 2016).

Hence, its interest on promoting a sharp increase on power production from renewable sources, being Italy considered one of the European countries (together with France, Germany, Sweden, Finland, Spain and United Kingdom) with the main bioenergy markets in 2020 (Calcante et al., 2018; Scarlat et al., 2013).

Poplar and willow are short rotation coppice-species most cultivated in Italy, specially in Po Valley (Northern Italy), for bio-energy and industrial (e.g., pulpwood and paper) purposes (González-García et al, 2012; Bacenetti et al., 2016). Poplar and willow cultivation (either at short rotation or very short rotation forestry regimes, SRF and VSRF respectively) includes activities such as harvesting and biomass collection, which are repeated in different times depending on the cultivation regime. Both activities involve the production of leaves and stools that, usually, remains in the plantation as nutrient and carbon supplier (González-García et al., 2012). Nevertheless, they could be used for bio-energy applications (Muth et al., 2013).

Traditional poplar plantation also exists in Italy mainly in Po Valley mostly destined to roundwood production for furniture sector (Verani et al., 2017). It involves a non-intensive management regime involving the production of potential woody biomass with only one harvesting event as difference to SRF and VSRF regimes.

In the case of Italy, forests are widespread in all the regions of the country being destined to firewood and roundwood production (Proto et al., 2017). Forestry with 10,467,000 ha cover about 34.7% of Italy (INFC, 2015). Although a variety of management systems exist for forests, shelter cut (high forest) in combination with natural regeneration is widespread. In this case, woody residues (mainly tops and brances), produced during logging operations, can be used for bio-energy applications.

In this study, the production of electricity and heat in Italy from wood based biomass either from forest and from agricultural activities has been analysed considering different production scenarios and final uses. The interest behind this study is the promoting use of biomass in small combustion installations in Italy as substitute for fossil fuels (Benetto et al., 2004; Caserini et al., 2010). Biomass from VSRF poplar and willow stands as well as residues from natural forests and from traditional poplar plantations have been considered for analysis. Attention has been paid on dedicated energy crops (i.e., willow and poplar) due to the current Italian interest on biomass power plants.

The results have been also compared with the conventional Italian scenario considering the current Italian electricity profile and heat production from natural gas. The assessment has been performed by applying Life Cycle Assessment (LCA) methodology in an attributional approach and a cradle-to-power plant gate perspective. A comprehensive and transparent analysis has been performed to facilitate comparisons between the proposed bio-energy scenarios.

2. Materials and methods

Life Cycle Assessment (LCA) is a widely used and standardised tool for the systematic evaluation of environmental aspects of a production system through all stages of its life cycle (ISO 14040, 2006). It is considered an ideal instrument to evaluate the environmental dimension of sustainability. Numerous studies related to bio-energy production have been also used this methodology to assess their environmental consequences (Benetto et al., 2004; Keoleian and Volk, 2005; Caserini et al., 2010; Cherubini and Strømman, 2011; González-García et al., 2014; Asdrubali et al., 2015; Patel et al., 2016). Within these studies, special attention was paid into liquid fuels production being the number of published studies focused on heat and power generation slightly lower (Cherubini and Strømman, 2011). However, its applicability in this area has been entirely demonstrated.

2.1. Goal and scope definition

This study aims to assess and compare the environmental consequences and energy requirements associated with the production of bio-energy (heat and power) for district heating systems and national grid suply from different biomass sources including energy crops derived from VSRF and forest residues. Biomass combustion is the simplest thermochemical conversion technology being heat and power (under co-generation regime) the main co-products of direct combustion of lignocellulosic material (Patel et al., 2016). Thus, different scenarios have been proposed for assessment trying to identify hotspots and differences.

In addition and as reference system for the comparison of the results, the production of heat considering a fossil source (i.e., natural gas) in a domestic boiler in the domestic sector as well as electricity production in the Italian national grid have been considered within the analysis to be compared with the designed scenarios proposed for analysis. The rationale behind this consideration is that the bio-energy modelled scenarios allow saving of both fossil based production routes.

2.2. Functional unit

The functional unit considered to report the environmental profile is 1 kWh of electricity (kWhe) produced in a combined heat and power plant (CHP) based on an Organic Rankine Cycle (ORC) and with an energy efficiency of 20% in the ORC and 85% in the boiler, regardless the biomass source. The consideration of an energy-based functional unit has also been considered in previous LCA studies available in the literature (González-García et al. 2014) allowing the comparison with alternative production systems with independence of the feedstock used (Muench and Guenther, 2013).

2.3. System boundaries definition

An attributional cradle-to-gate approach has been followed in this study in all the scenarios proposed for analysis i.e., from raw materials extraction till the production of energy in the plant. Thus, the further use of the produced electricity has been excluded from analysis. The CHP is mainly constituted by two different sections. The first one is characterised by a biomass boiler (thermal power of 6.047 MW) fed with the woody biomass while the second section is mainly constituted by a ORC turbine with 1 MW of electric power. The Organic Rankine Cycle's principle is based on a turbogenerator working as a conventional steam turbine to transform thermal energy into mechanical energy and finally into electric energy. Instead of generating steam from water, the ORC system vaporises an organic fluid, characterised by a molecular mass higher than that of water (e.g., 152.9 for the HCFC-123), which leads to a slower rotation of the turbine, lower pressures and no erosion of the metal parts and blades.

At the CHP plant, the heat produced by the biomass boiler is transferred, using a diathermic oil (310-315 °C and 6 bar), to the ORC where is transformed in mechanical power and, through a electrical generator, in electricity. More in details, the organic fluid vapor rotates the turbine, which is directly coupled to the electric generator. Afther that, the exhaust vapor flows through the regenerator, where it is then condensed in the condenser and cooled by the cooling circuit. The thermal energy used in the district heating is recovered at the condenser. The district heating distribution grid is 1.5 km-long and a lifespan of 30 years was considered.

Figure 1 displays the foreground system boundaries corresponding to the four scenarios considered as base case studies. All electricity produced is directly fed into the Italian national grid. There is no recycling to satisfy electricity demand in the CHP unit due to technical reasons (the different electric devices for biomass loading, exhaust gas treatment, ash removal etc. must operate also when the ORC does not work for maintenance or breakages) (Fiala, 2012). Regarding heat, only the 16% of all heat produced in sent to a nearby hospital and school to satisfy heating requirements. The remaining 84% is considered as a waste since it is not recovered.

<**Figure 1** around here>

Scenario 1 (Sc1) is based on the consideration of residues from natural regeneration forestry and industrial activities as feedstock. These stands are naturally managed i.e., they are handled under low management intesity. The forest stands are untouched forests with a history of limited management (Buiteveld et al., 2007). Thus, no activities are performed throughout the lifespan (> 60 years) after initially diversifying the forest structure (Buiteveld et al., 2007). Biomass extracted is mostly dedicated as raw material (roundwood) for furniture sector. Wood residues such as tops and branches are recovered in the harvesting activities as well as throughout the lifespan of the plantation. In this scenario, these residues are considered as raw material for bio-energy production (see **Figure 1a**). Firstly, wood residues are chipped into the forestry using a self-propelled chipper and after they are transported to the bio-energy plant. Residues from furniture production activities are also considered and chipped in the plant. In this scenario, the entire environmental burdens of the multifunctional process (only derived from logging operations) are allocated to the main product (roundwood). Therefore, wood residues are considered waste and free of environmental burdens except with regard

to forest residues chipping and chip wood transport. This approach is sometimes deemed reasonable specially if the demand of the co-products has no influence on te production capacity of the system (Sandin et al., 2015).

Scenario 2 (Sc2) and Scenario 3 (Sc3) consider the biomass from VSRF stands of poplar and willow species, respectively, as feedstock for heat and power generation (see **Figure 1b**). The management of VSRF plantations has been considered within the system boundaries considering all processes performed in the stands from field preparation and management, harvesting and field recovery at the end of the lifespan of the plantations (approximately ten years in both species) in agreement with González-García et al. (2012) and Bacenetti et al. (2016). It is important to highlight that as difference to forest stands dedicated to roundwood production for industrial uses, all the produced biomass (including wood residues such as branches, stools and leaves) is recovered and sent to bio-energy production. The total trees are felled, and directly chipped on the field by means of a forage harvesters equipped for a specific header.

Scenario 4 (Sc4) is based on the valorisation of forest residues derived from traditional poplar stands which are mainly dedicated to the production of roundwood for pulpuwod and furniture production. Wood residues are managed in the same way as in Sc1, being chipped in the power plant before their combustion in the CHP unit. All forest operations carried out in the stands have been computed within the foreground system boundaries (see **Figure 1c**). Thus, organic fertilisation, ploughing, harrowing and planting have been considered as part of field preparation activities. Herbicide and pest control, mechanical weed control, irrigation (if necessary depending on the climatic conditions) and harvesting at the end of the lifespan (12 years) have been included in stand management and harvesting stage. Finally, field recovery after the harvesting is also performed with an forestry shredder. In this scenario, economic allocation has been assumed to share out the environmental burdens derived from forest activities between both co-products (roundwood, 55 €/t and wood residues 4.5 €/t) (Lovarelli et al., 2018). The rationale behind this approach is the market interest on both co-products.

Within each scenario, avoided processes have also been accounted since it is assumed that biomass combustion allows savings of natural gas for heat production. Therefore, the production of the amount of heat sent for final use in the surroundings (hospital and school) considering the combustion of natural gas in a domestic boiler has been contemplated

2.4 Hypotheses and Life cycle inventory

A reliable environmental assessment requires the collection of high quality inventory data. The biomass conversion process into heat and power present a wide range of material and energy exchanges with the technosphere and the environment. Thus, masss and energy flows need to be estimated as well as avoided impacts related to the processes involved in each scenario. Therefore, the mass and energy flows corresponding to the foreground systems (**Figure 1**) have been modelled and quantified for each type of feedstock. A summary of the most relevant inventory data per scenario is reported in **Table 1**.

<**Table 1** around here>

The estimation of the amounts of biomass necessary to produce 1 1 kWhe (functional unit) has followed the method defined by Butnar et al. (2010) based on the power plant capacity, the operation hours, the efficiency, the low heating value (LHV) and moisture content for each biomass source (**Table 2**).

<**Table 2** around here>

Regarding the production of the feedstocks, forestry residues production (Sc1) has been excluded from the system boundaries due to the allocation of all environmental burdens derived from forestry management to the roundwood (main product). Regarding VSRF poplar and willow biomass production (Sc2 and Sc3, respectively), inventory data regarding forest activities performed in the stands have been taken from González-García et al. (2012) and Bacenetti et al.(2016), respectively. In the case of traditional poplar stands, their management has been included within the system boundaries of Sc4. The following inventory data have been accounded for: the amount of machinery needed for each specific forest process (tractors and forest equipment), fuel consumption (and production) in all forest activities (considering operating rate and diesel consumption) as well as the production of all the agro-chemical inputs to the field, such as herbicides (glyphosate and gluphosinate-ammonium) and pesticide (Deltamethrin). Regarding fertilisation, it is performed using cattle manure considered as a waste in farming activities. Therefore, impacts from background activities involved in the production of this organic fertiliser have been excluded from the system boundaries. Derived emissions from organic fertiliser and agro-chemicals application have been quantified as well as combustion emissions from diesel use in the machinery. A summary of main inventory data corresponding to traditional poplar stands is reported in **Table 3**.

<**Table 3** around here>

Concerning the biomass supply till the power plant, it has been computed in the analysis. In all the scenarios it has been assumed that the power plant is placed within the Lombardy region. This region has gained relevance in the last years due to the establishment of several biomass thermoelectric power plants (Bergante et al., 2010; Lijó et al., 2017). Forestry wood residues are transported by lorries (16-32 t) an average distance of 800 km (from forestry located in Southern Italy). Poplar and willow plantations are extended around the Po Valley (Lombardy region). Thus, an average transport distance of 35 km by lorry (16-32 t) has been assumed in both cases. In the case of wood residues from traditional poplar stands, 20 km has been considered. Diesel lorries have been used for biomass transport in all the scenarios.

Although primary data should be used whenever possible, it is sometimes necessary to turn to secondary ones. In this study, information regarding the diesel consumed in the chipping process (Sc1 and Sc4), electricity required in the CHP unit (all scenarios) as well as ashes disposal in a sanitary landfill, has been taken from the Ecoinvent ® database (Weidema et al., 2013).

Moreover, inventory data corresponding to the background system, which involves the production of utilities (electricity), other inputs to the foreground system (agro-chemicals, water, machinery) and infrastructure (e.g., the distribution grid) have been taken from a pre-existing database and the literature as detailed in **Table 4**.

<**Table 4** around here>

Indirect emissions generated from all the different processes involved have been also included. In this sense, combustion emission factors corresponding to the biomass burning in the power plant have been taken from the IPCC guidelines (IPCC, 2007) and EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2013).

2.5. Life Cycle Impact Assessment method

Among the steps defined within the life cycle impact assessment stage of the standardised LCA methodology, only classification and characterisation stages were undertaken (ISO 14040, 2006). The characterisation factors reported by the ReCiPe Midpoint (H) 1.12 method (Goedkoop et al. 2013a) were considered to estimate the environmental impacts in this study. According to LCA experts, this method is the most updated alternative that provides a common framework in which both midpoint and endpoint indicators can be used, as opposed to similar methodologies to date (PRé Consultants 2017)The implementation of the Life Cycle Inventory data has been performed in the SimaPro v8.2 (PRé Consultants, 2017) software (Goedkoop et al., 2013b). The following impact categories were selected to evaluate the environmental profile of the different scenarios: climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF) and fossil depletion (FD). The choice of these impact categories for the environmental study is based on the fact that they are the most common categories reported in LCA studies of bioenergy systems (Cespi et al., 2014; Lijó et al., 2017).

3. Environmental results and discussion

The scenarios proposed for assessment have been analysed from an environmental perspective in order to identify their hotspots as well as to compare their profiles with the aim of identifying differences. The characterisation results are detailed in **Table 5**.

<**Table 5** around here>

Figure 2 displays the comparative profiles between the scenarios under assessment and the reference system (i.e., electricity production under the Italian electric profile). According to the results, all of the evaluated bio-energy scenarios involve environmental beneftis in terms of impact categories such as CC and FD. According to previous studies, the substitution of fossil fuels with biomass sources to

produce energy requirements implies a saving of GHG emission as well as fossil fuels depletion (Caserini et al., 2010; González-García et al., 2014). Although a detailed analysis per scenario is reported below, the rationale behind these environmental benefits is linked to the avoided process included within the system boundaries. Regardless the scenario, electricity produced together with heat subsequently used (~16%) involve the avoidance of producing it from conventional way that is, from the combustion of natural gas in an domestic boiler.

<**Figure 2** around here>

A discussion for each impact category is presented in the following sections. **Figure 3** depicts the main activities or processes for each impact category analysed and bio-energy scenario, as resulting from the contributions analysis. It is important to note that the amount of heat and electricity produced in all scenarios is exactly the same (see **Table 1**). Therefore, the contribution from the avoided process is also the same in terms of characterisation results. Thus, differences on the profiles are directly linked to the differences on the foreground system. Positive values in **Figure 3** are indicative of environmental burdens, whereas negative values are indicative of environmental credits/benefits derived from avoided process.

<**Figure 3** around here>

3.1. Assessment per impact category

CC: In this impact category the CHP unit is considered as an environmental hotspot regardless the scenario under study. Although in Sc1, it is really important the effect of transport activities from forest site till the power plant, which could be expected due to the large transport distance (800 km). The contributions in the remaining scenarios from this process are not remarkable. However, attention should be paid to the feedstock production in Sc2 and Sc3 (and in Sc4 in a minor extent). In both cases, the biomass is specifically produced for bio-energy purposes under a VSRF regime involving numerous forestry activities and diesel requirements. In Sc4, poplar biomass is produced under a traditional regime, less intensive than in the other two and biomass is cultivated with other uses (e.g. furniture) being only the residues considered for bio-energy purposes. Production of electricity requirements in the CHP plant, which are directly taken from the Italian grid, is responsible for more than 85% of total GHG emissions derived from this unit. In Sc2, Sc3 and Sc4, emissions from diesel combustion in forest machinery are behind the contributions from feedstock production in this impact category.

TA: Once again the CHP unit is the key factor responsible for the substances that contribute to this impact category. In this category, not only the production of electricity requirements is remarkable but also the emissions produced from diesel combustion in internal machines used in the power plant. Their contributing ratios add up to 29% and 69% of total effect from CHP unit. Forestry activities involved in the production of poplar and willow biomass (Sc2 and Sc3) are responsible for 57% and 48% of acidifying substances produced all over the life cycle, respectively. Emissions from diesel use in forest machines as well as diffuse emissions derived from manure and mineral fertiliser application dominate the acidifying emissions from that stage.

FE: In this impact category the hotspot depends on the scenario assessed. In Sc1, transport activities are responsible for 80% of eutrophying emissions. Howevee, in scenarios based on the use of energy dedicated crops (Sc2 and Sc3), feedstock production related activities are behind their outstanding contributing ratio mostly due to the application of manure as organic fertiliser and derived fertilising emissions. On the contrary, in Sc4 the hotpost is the CHP unit (~63% of total contributing substances) due to cleaning chemicals used in the plant as well as the manufacturing and maintainance of the ORC unit.

ME: Scenarios based on the use of biomass from dedicated crops, i.e., poplar and willow respectively for Sc2 and Sc3, report the worse profile in terms of this impact category being up to 10 and 7 times higher than Sc1. The rationale behind these results is the production of feedstock (see **Figure 3**). According to the cultivation description, stands are managed under very short rotation regime involving numerous fertilisation activities. Cattle manure together with urea are applied in both crops according to González-García et al. (2012) and Bacenetti et al.(2016).. Thus, diffuse emissions from fertilising dominate the contributions to this category mainly due to NH_3 emission derived from nutrient application. In a minor extent, NO_x emissions derived from diesel combustion in the agricultural machines also are responsible substances. Regarding Sc4, the profile is lower than Sc2 and Sc3 bieng also the feedstock production related activities the main hotspot. However, the cultivation under low intensive conditions and the considered allocation approach (only residues are managed) are responsible of the best result. In the case of Sc1, activities involved in the power plant constitute the key factor (~80% of total contributing substances). Direct N-based emissions derived from the combustion of the biomass in the boiler are the hotspot being responsible of 82% of contributions from CHP plant.

HT: As depicted in Figure 3, scenario focused on bio-energy production from forestry residues (Sc1) reports the worse profile being Sc2, Sc3 and Sc4 around 59%, 64% and 77% smaller than Sc1. The distribution of feedstock by diesel lorry till the power plant gate is the key issue in Sc1 responsible for 67% of contributing substances. In the reaming scenarios, activities carried out in the CHP plant can be considered as hotspot with contributing ratios of 57%, 61% and 80%. Emissions from the biomass combustion in the boiler (such as heavy metals and nitrogen oxides) are behind the power plant effect.

POF and *PMF*: Results in these impact categories are directly related as depicted in Figure 3. POF takes into account the emissions into air of substances (e.g. nitrogen dioxide, nitrogen oxides, sulfur oxides or toluene) that produce photochemical smog. Regarding PMF, it considers the emission of particulates as well as sulfur oxides, nitrogen oxides and ammonia, which can also produce smog. Therefore, the profiles in both impact categories regardless the scenario analysed are almost identical. In all scenarios, emissions from biomass combustion (e.g., of particulates and nitrogen oxides) in the boiler within the power plant can be considered as the hotspot. However, in Sc1 it is also outstanding the effect from biomass distribution. In the case of Sc2 and Sc3, agricultural activities required to the biomass production are remarkable in both impact categories mainly due to the use of diesel machines.

FD: This impact categories represents the consumption of fossil resources all over the life cycle. Transport activities is the hotspot in Sc1 which could be expected due to the large delivery distance (800 km), being negligible in the remaining scenarios. Diesel requirements in agricultural activities in the hotspot in Sc2 and Sc3. Numerous large machines are involved in the cultivation of VSRF poplar and willow being harvesting and chipping on field (combine harvester) the main responsible ones.

3.2. Comparative assessment between scenarios

Figure 2 displays the comparative profiles per impact category between the scenarios considered for analysis and the reference system. As expected, improvements are achieved per functional unit (1 kWhe) when bio-energy systems are proposed expefically in terms of GHG and fossil fuels savings (CC and FD respectively). In this sense, the use of wood residues from traditional poplar stands derives on the best profiles not only in terms of CC and FD but also in PMF and TA. The short transport distance considered for the biomass supply (20 km) to the power plant as well as the low allocation ratio to share the impact from poplar stands between the residues and the main product (i.e., roundwood) are behind these results in spite of producing the largest amount of ashes. According to the results, effect on the profiles, regardless the scenario, from ashes disposal in a landfill is negligible (see **Figure 3**). Landfilling is a common practice in Italy, and harmful effects may be caused by the release of heavy metals (Cespi et al., 2014) as well as unpleasant odors and groundwater pollution from leachate formation if not well controlled (Calvo et al., 2005).

In the remaining impact categories and in general lines, the results do not benefit bio-energy systems, achieving the reference system (i.e., electricity produced under the Italian electric profile) the best profiles (specifically in HT, ME and FE) in line with other studies (Caserini et al., 2010). Biomass combustion is associated with higher impacts than fossil fuels use, due to thigher emissions of toxic substances. Background processes are also implicated in these results due to agricultural activities.

Finally, normalisation factors established by ReCiPe Midpoint (H) 1.12 method (Goedkoop et al. 2013a) have been considered in order to obtain an index per scenario and to perform a direct comparsion between scenarios. **Figure 4** depicts the comparative profiles. According to it, the indexes show that shifting from fossil fuels based energy by renewable one can be or not more environmental friendly and an specific analysis is mandatory due to the influence of assumptions and bio-energy system characteristics. The use of dedicated crops (Sc2 and Sc3) contribute to increase the environmental index as well as the biomass distribution from large distances (Sc1) even though residues were managed. However and although the use of wood residues for power and heat production is interesting from environmental and energy perspectives, further analysis should be focused on the availability of these sources and their ability to meet energy requirements. The results reported in this study support the idea - as also reported in other studies (Caserini et al., 2010; Cespi et al., 2014; González-García et al., 2014) that the use of agricultural and forest residues could provide a potential available raw material for bio-energy production. However, more research and technological development is required to promote their use. Moreover, dedicated crops are interesting due to their high production yields, guaranteed availability and added benefits such as contributions to rural development, landscape diversity and reduced erosion potential (Heller et al., 2004). However, more exploration is necessary to reduce the impacts derived from background processes involved in agricultural activities (Bacenetti et al., 2018).

<**Figure 4** around here>

3.3. Alternative scenarios

In the scenarios considered for analysis, only 16% of total heat produced in the CHP plant is finally used being the remaining 84% wasted into air. However, it should be interesting the recovery and final use of the total heat produced (e.g., it could be considered in heating systems in the surrounding areas). Thus, 14.11MJ should be produced per kWhe, which should avoid the production of that amount of heat from natural gas. Moreover, electricity requirements in the power plant are directly taken from the national grid. However, it could be feasible to satisfy its electricity requirements (0.24 kWhe) recycling it from the electricity produced, being 0.76 kWhe sent to the national grid. The consideration of both hypothesis has been considered for analysis and **Figure 5** displays the comparative profiles between the bio-energy scenarios and the alternative ones considing a normalised index. Taking in mind the results, it is demonstrated the environmental benefits of producing both heat and electricity from wood residues and dedicated crops in comparison with the current national electric profile. In this sense, environmental credits could be achieved mostly using wood residues from tradional poplar stands and willow-based biomass.

<**Figure 5** around here>

3.4. Transport effect

The effect of feedstock distribution activities have been remarkable in Sc1 where around 800 km have been assumed as transport distance. It is a reality since forest stands are widespread in Southern Italy.

However, the influence of transport distance on LCA results has just been considered in previous studies where power production was environmentally analysed (Nussbaumer and Oser, 2004; Caserini et al., 2010). In these studies, it was reported that large transport distances imply a high consumption of primary energy, which could be higher than energy produced.

According to INFC (2015), in Italy, forestry are widespread also in the Central Italy (Appennino and, in particular, Tuscany and Umbria regions) as well as in Northern Italy (e.g., Veneto, Trentino). Therefore, a comparative analysis has been performed to identify the benefits of processing forest residues from closer areas. Average transport distances of 300-350 km and 350-370 km have been assumed respectively for forestry residues distribution from Tuscany (ScA) and Northern Italy (ScB). **Figure 6** displays the comparative profiles considering the normalisation score. According to it, outstanding reductions of the environmental profile could be achieved of up to 40% in residues are delivered from Central Italy regions. Thus, transport distance plays a key role on the environmental profiles and could be decisive in decision making strategies.

<**Figure 6** around here>

4. Conclusions and future outlook

The results reported in this study support the idea that wood residues would be an interesting and potential raw material for bio-energy purposes although further research is required either from environmental and economic point of views. Wood residues from natural regerenation forest, industrial activities and traditional poplar stands seem to be favourable to dedicated energy crops in a global approach. Thus, it must be encouraged the use of forest and wood-processing residues as feedstock from a circular economy approach not only in the bio-energy sector but also in the latent bio-based industry.

The current efforts performed in recent years have given rise to numerous technological developments enhancing “closing the loop” strategies under a biorefinery concept through better recycling and re-using the waste streams. Wood-based residues availability and low associated costs in comparison with dedicated bio-energy crops support also their interest.

According to the main findings from this study, LCA methodology can be considered as a valuable and useful tool to support decision making strategies under an environmental approach, specifically for systems under development such as the ones reported in this study. However, additional research should be perfomed not only in the environmental pillar of the sustainability but also in the social and economic ones to obtain a full overview. Moreover, attention must be paid in these categories different than climate change and fossil depletion (the ones that are subject of great public debate), considerably affected by air pollutant emissions derived from biomass combustion mostly when dedicated energy crops are considered.

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Table 1. Foreground data summary for the production of heat and power from natural regeneration forestry residues (Sc1), VSRF poplar (Sc2) and willow (Sc3) biomass and residues from traditional poplar stands (Sc4)

	Sc1	**Sc2**	**Sc3**	**Sc4**
Inputs				
Materials				
Wood-based feedstock (kg)	1.94	2.53	2.55	2.52
Diesel -chipping (g)	2.13	--	--	1.92
Energy				
Electricity -CHP unit (kWh)	0.236	0.236	0.236	0.236
Transport				
Truck (kg·km)	1,550	88.6	89.1	50.5
Outputs				
Energy				
Electricity (kWh)	1.00	1.00	1.00	1.00
Heat to final use (MJ)	2.27	2.27	2.27	2.27
Emissions to air				
CO (g)	0.122	0.161	0.158	0.159
PM$_{2.5}$ (g)	0.061	0.080	0.078	0.079
NO$_x$ (g)	0.098	0.129	0.128	0.127
Heat -waste (MJ)	11.84	11.84	11.84	11.84
Waste to treatment				
Ash to sanitary landfill (g)	77.5	38.0	39.4	93.4
Avoided products				
Electricity -Italian profile (kWh)	1.00	1.00	1.00	1.00
Heat from natural gas (MJ)	2.27	2.27	2.27	2.27

Table 2. Low heating values (LHV) specifications for the biomass sources under assessment

Biomass source	**Moisture content**	**LHV**	**Source**
Wood-based residues	35%	5.27 kWh·kg dm^{-1}	Proto et al. (2017)
VSRF poplar biomass	45%	5.27 kWh·kg dm^{-1}	Bacenetti et al. (2016)
VSRF willow biomass	45%	5.25 kWh·kg dm^{-1}	Bacenetti et al. (2016)
Poplar residues	41%	4.88 kWh·kg dm^{-1}	Direct estimation

kg dm= kg dry matter

Table 3. Primary inventory data summary associated with the production of wood-based residues from traditional poplar stands

Field preparation stage	
Inputs	
Diesel (kg/ha)	80
Cattle manure (t/ha)	50
Management stage	
Inputs	
Diesel (kg/ha)	650
Glyphosate and gluphosinate-ammonium - herbicide (kg/ha)	5
Deltamethrin - pesticide (kg/ha)	4
Water (m^3/ha)	4000
Harvesting and Soil recovery stage	
Inputs	
Diesel (kg/ha)	250
Outputs	
Poplar roundwood (t/ha)	120
Poplar residues (t/ha)	40

Table 4. Description of the main Ecoinvent ® database version 3.2 processes (Weidema et al., 2013) and other literature sources considered in this study for the background processes

Input	**Process**
Electricity	Electricity, medium voltage {IT}| market for | Alloc Rec, U
Heat	Heat, central or small-scale, natural gas {RER}| market group for | Alloc Def, U
Water	Tap water {Europe without Switzerland}| market for | Alloc Rec, U
Glyphosate	Glyphosate {GLO}| market for | Alloc Def, U
Deltamethrin	Deltamethrin {GLO}| market for | Alloc Def, U
Ash disposal	Wood ash mixture, pure {RoW}| treatment of, sanitary landfill | Alloc Def, U
Chipping (diesel)	Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | Alloc Def, U
CHP (biomass)	Butnar et al. (2010)
CHP (emissions)	IPCC (2007) and EMEP/EEA (2013)
Diesel lorry (16-32t)	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U
VSRF poplar cultivation	González-García et al. (2012)
VSRF willow cultivation	Bacenetti et al. (2016)

Table 5. Characterisation results corresponding to each bio-energy scenario under assessment per functional unit (1kWhe)

Impact category	**Unit**	**Sc1**	**Sc2**	**Sc3**	**Sc4**
Climate Change (CC)	kg CO_2eq	$2.65\cdot10^{-1}$	$1.59\cdot10^{-1}$	$1.22\cdot10^{-1}$	$6.02\cdot10^{-2}$
Terrestrial Acidification (TA)	kg SO_2eq	$2.23\cdot10^{-3}$	$4.50\cdot10^{-3}$	$3.64\cdot10^{-3}$	$2.10\cdot10^{-3}$
Freshwater Eutrophication (FE)	kg Peq	$2.21\cdot10^{-5}$	$1.65\cdot10^{-5}$	$1.27\cdot10^{-5}$	$6.03\cdot10^{-6}$
Marine Eutrophication (ME)	kg Neq	$1.08\cdot10^{-4}$	$5.72\cdot10^{-4}$	$4.24\cdot10^{-4}$	$3.13\cdot10^{-4}$
Human Toxicity (HT)	kg 1,4-DBeq	$9.31\cdot10^{-2}$	$4.59\cdot10^{-2}$	$4.16\cdot10^{-2}$	$3.17\cdot10^{-2}$
Photochemical Oxidant Formation (POF)	kg PM10eq	$2.25\cdot10^{-3}$	$2.66\cdot10^{-3}$	$2.37\cdot10^{-3}$	$1.84\cdot10^{-3}$
Particulate Matter Formation (PMF)	kg NMVOC	$9.08\cdot10^{-4}$	$1.19\cdot10^{-3}$	$1.01\cdot10^{-3}$	$6.70\cdot10^{-4}$
Fossil Depletion (FD)	kg oil eq	$8.38\cdot10^{-2}$	$3.91\cdot10^{-2}$	$2.77\cdot10^{-2}$	$7.69\cdot10^{-3}$

Figure 1. System boundaries for the modelled bio-energy systems producing the same amount of bio-energy (heat and electricity). The bio-energy chain based on residues from natural regeneration forestry (Sc1) is represented in the upper part (a), system based on energy-dedicated poplar (Sc2) and willow (Sc3) biomass is displayed in central part (b) whereas system based on traditional poplar cultivation residues (Sc4) is depicted in the lower part (c).

Figure 2. Comparative profiles between the scenarios under study and the reference system. Acronyms: Sc1 – wood-based residues; Sc2 – VSRF poplar biomass; Sc3 – VSRF willow biomass; Sc4 – traditional poplar residues; ScR – reference system.

Figure 3. Process contributions to impact categories per scenario; Acronyms: Sc1 – wood-based residues; Sc2 – VSRF poplar biomass; Sc3 – VSRF willow biomass; Sc4 – traditional poplar residues.

Figure 4. Comparative normalization indexes between the scenarios under study and the reference system. Acronyms: Sc1 – wood-based residues; Sc2 – VSRF poplar biomass; Sc3 – VSRF willow biomass; Sc4 – traditional poplar residues; ScR – reference system.

Figure 5. Comparative normalization indexes between the scenarios under study (Sc1-Sc2-Sc3-Sc4), the reference system (ScR) and alternative scenarios recovering 100% heat and recycling electricity to satisfy electric requirements (Sc1a-Sc2a-Sc3a-Sc4a).

Figure 6. Comparative normalization indexes between bio-energy production from wood-based residues from natural regeneration forestry considering different transport distances. Acronyms: Sc1 – 800km; ScA – 325km; ScB – 360km.

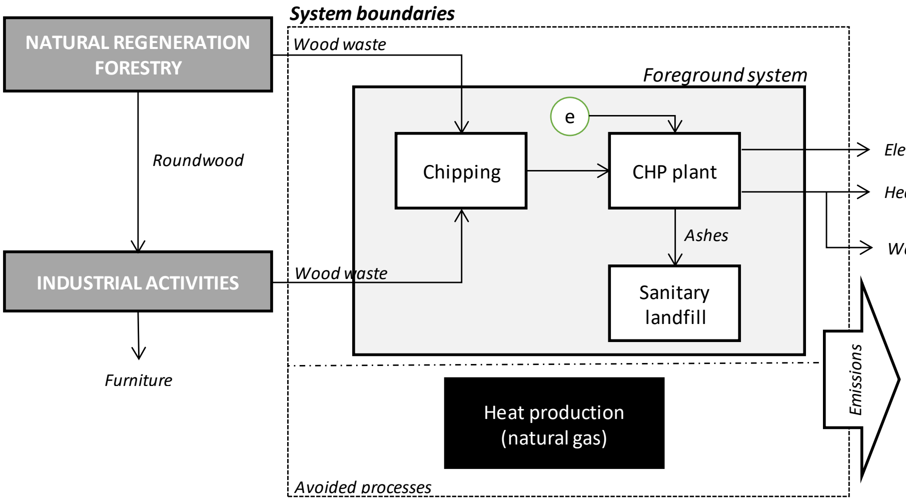

Figure 1a

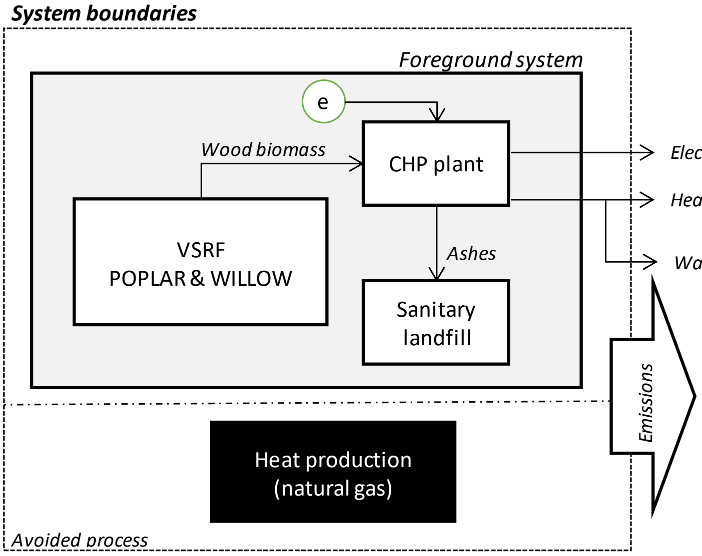

Figure 1b

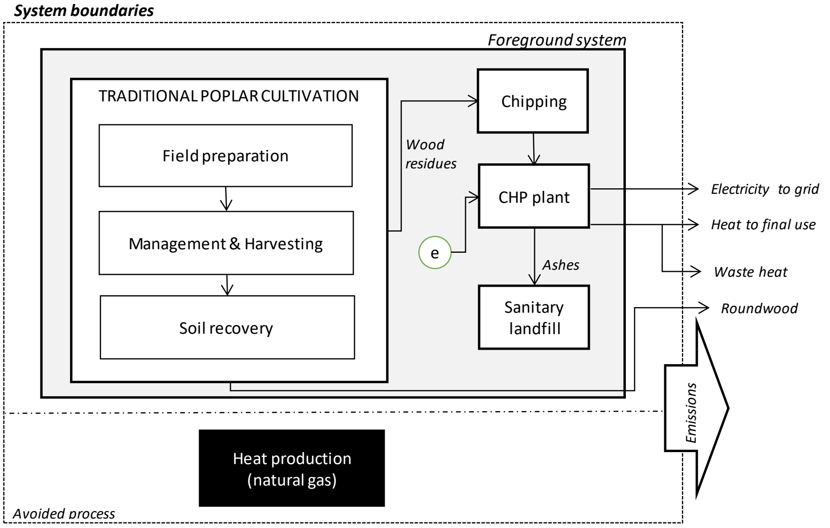

Figure 1c

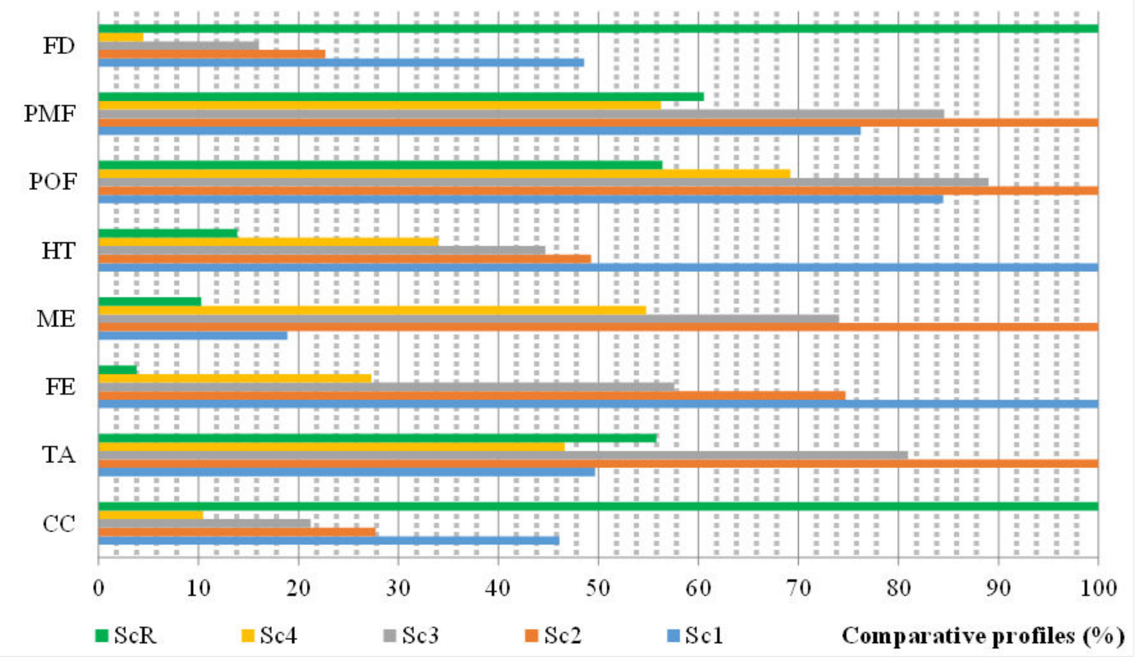

Figure 2

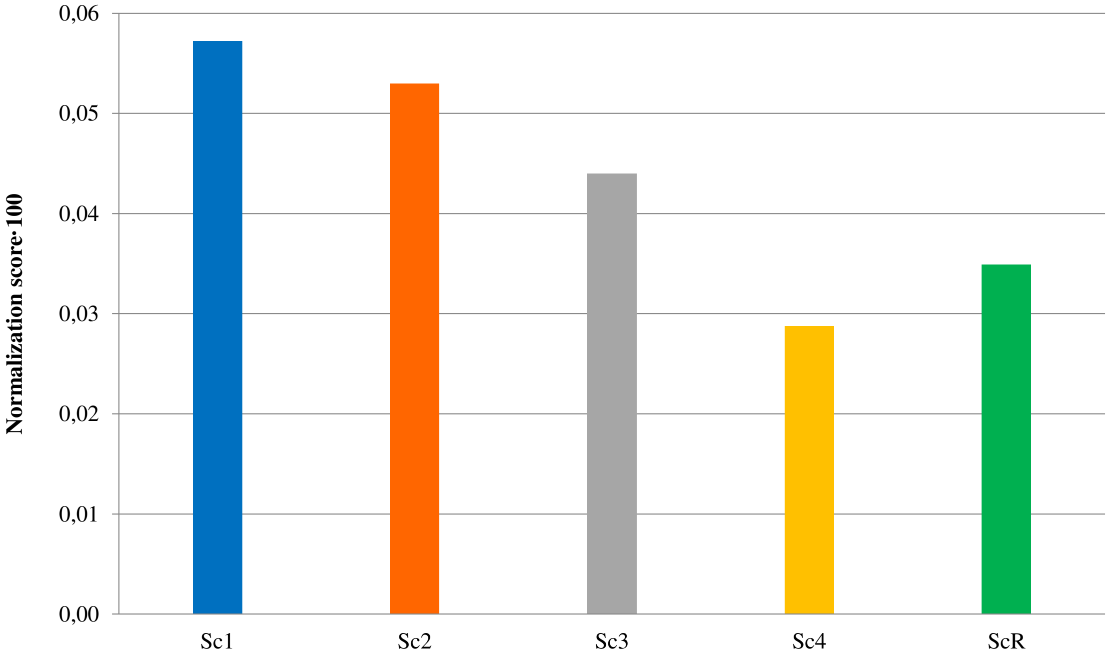

Figure 4

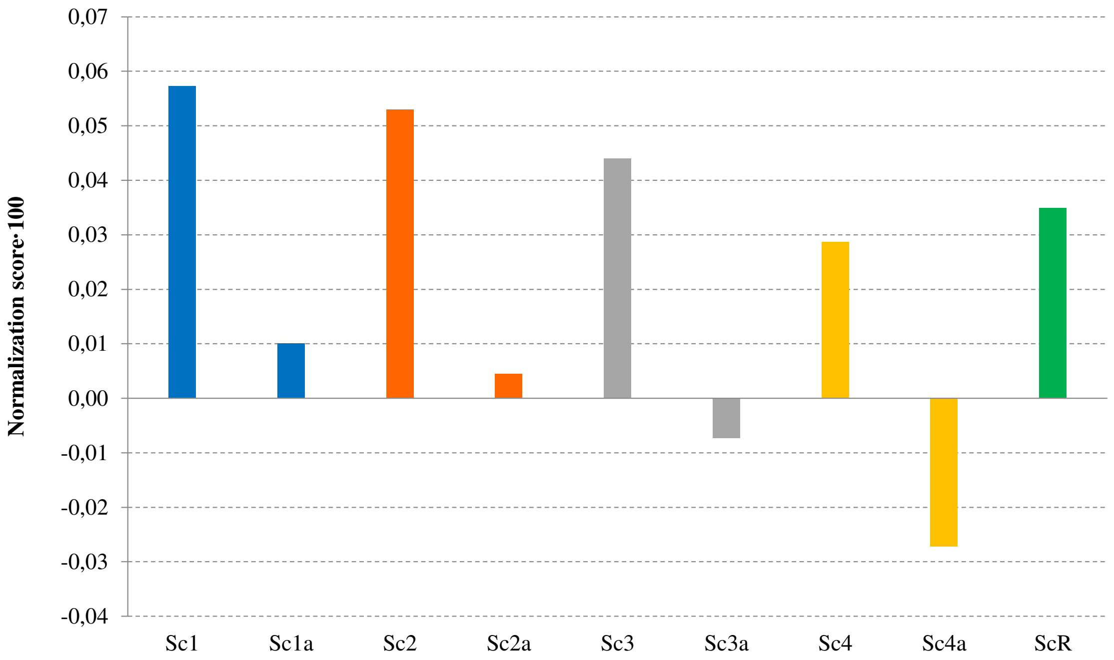

Figure 5

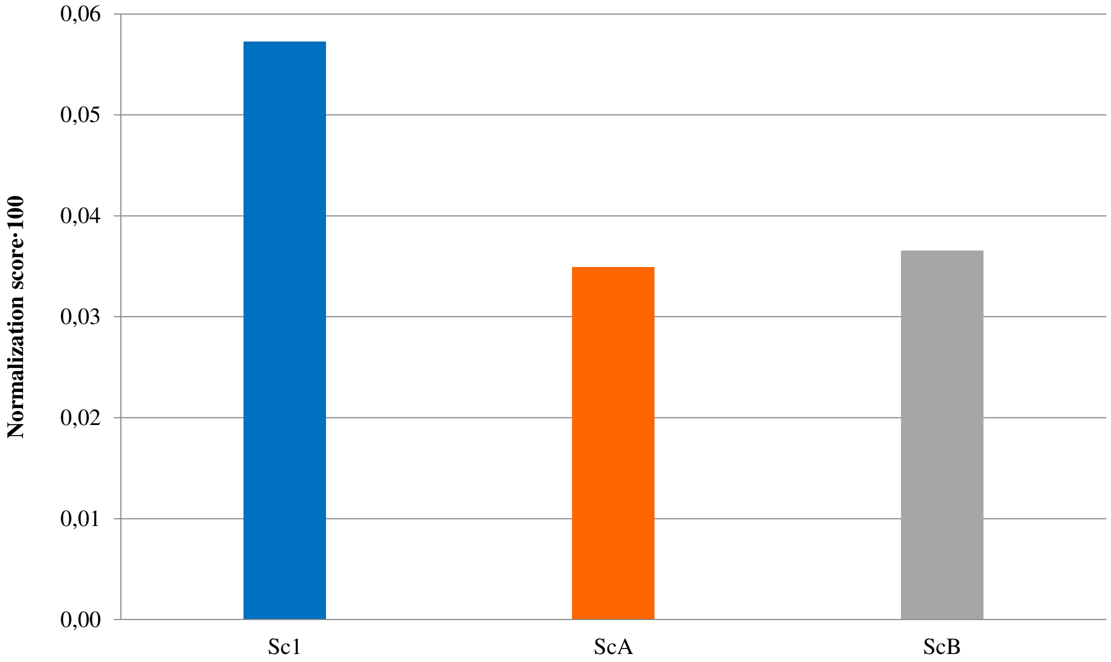

Figure 6