

## 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

28 residues would be an interesting and potential feedstock for bio-energy purposes although further  
29 research is required specifically with the aim of optimizing biomass supply distances.

30

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

32 Willow

33

## 34 **1. Introduction**

35 Mitigation of climate change and derived effects is a global challenge (IPCC, 2007) motivating the  
36 international community to introduce easing strategies (Oreggioni et al., 2017). Therefore, European  
37 Union's energy and climate change plans try to avoid the use of fossil-based energy by means of the  
38 promotion of bio-energy (Directive 2009/28/EC; European Commission, 2018). In this sense, energy  
39 industries have contributed to ~32% of global CO<sub>2</sub> emission over the last 20 years (Janssens-  
40 Maenhout et al., 2012; Oreggioni et al., 2017) as well as heating and cooling processes are  
41 responsible for approximately 50% of the final European energy demand (Tsupari et al., 2017). Finally  
42 it is important to note that, in Europe, fuel combustion in energy industries is the most important  
43 contributor to anthropogenic climate change, with 28.5% of total greenhouse gases (GHG) emissions  
44 in 2015 (Eurostat, 2018).

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

53 Bio-energy systems include a full range of products such as bio-ethanol, bio-diesel, biogas, electricity  
54 and heat, all of them from a large range of potential feedstocks – e.g., wood from forests, crops,  
55 seaweed and animal, forest and agricultural wastes (González-García et al., 2014). Moreover, biomass  
56 as its primary product is a versatile energy source that can be stored and converted to energy on-  
57 demand (De Meyer et al., 2014). The waste-to-energy concept is being highly promoted as a part of  
58 the efforts into sustainable development in energy sector (Ferreira et al., 2017). The use of forest and  
59 agricultural residues as well as other biomass waste from agricultural and industrial activities for bio-  
60 energy production (mainly electricity and heat) plays a key role in the energy system (Eurostat, 2015)  
61 and it is expected to increase over the next few years. According to MISE (2012), the share of energy

62 from renewable energy sources should reach in 2020 the 17% of the total national energy  
63 consumption. In this sense, there is a clear potential for increased use of wood for energy purposes in  
64 the EU, mostly related to forest residues and complementary fellings (SFC-WGII, 2008).

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

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

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

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

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

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

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

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

112 In this study, the production of electricity and heat in Italy from wood based biomass either from  
113 forest and from agricultural activities has been analysed considering different production scenarios and  
114 final uses. The interest behind this study is the promoting use of biomass in small combustion  
115 installations in Italy as substitute for fossil fuels (Benetto et al., 2004; Caserini et al., 2010). Biomass  
116 from VSRF poplar and willow stands as well as residues from natural forests and from traditional

117 poplar plantations have been considered for analysis. Attention has been paid on dedicated energy  
118 crops (i.e., willow and poplar) due to the current Italian interest on biomass power plants.

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

124

## 125 **2. Materials and methods**

126 Life Cycle Assessment (LCA) is a widely used and standardised tool for the systematic evaluation of  
127 environmental aspects of a production system through all stages of its life cycle (ISO 14040, 2006). It  
128 is considered an ideal instrument to evaluate the environmental dimension of sustainability. Numerous  
129 studies related to bio-energy production have been also used this methodology to assess their  
130 environmental consequences (Benetto et al., 2004; Keoleian and Volk, 2005; Caserini et al., 2010;  
131 Cherubini and Strømman, 2011; González-García et al., 2014; Asdrubali et al., 2015; Patel et al.,  
132 2016). Within these studies, special attention was paid into liquid fuels production being the number  
133 of published studies focused on heat and power generation slightly lower (Cherubini and Strømman,  
134 2011). However, its applicability in this area has been entirely demonstrated.

135

### 136 **2.1. Goal and scope definition**

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

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

149

## 150 **2.2. Functional unit**

151 The functional unit considered to report the environmental profile is 1 kWh of electricity (kWh<sub>e</sub>)  
152 produced in a combined heat and power plant (CHP) based on an Organic Rankine Cycle (ORC) and  
153 with an energy efficiency of 20% in the ORC and 85% in the boiler, regardless the biomass source.  
154 The consideration of an energy-based functional unit has also been considered in previous LCA  
155 studies available in the literature (González-García et al. 2014) allowing the comparison with  
156 alternative production systems with independence of the feedstock used (Muench and Guenther,  
157 2013).

158

## 159 **2.3. System boundaries definition**

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

171 At the CHP plant, the heat produced by the biomass boiler is transferred, using a diathermic oil (310-  
172 315 °C and 6 bar), to the ORC where is transformed in mechanical power and, through a electrical  
173 generator, in electricity. More in details, the organic fluid vapor rotates the turbine, which is directly  
174 coupled to the electric generator. Afther that, the exhaust vapor flows through the regenerator, where it  
175 is then condensed in the condenser and cooled by the cooling circuit. The thermal energy used in the  
176 district heating is recovered at the condenser. The district heating distribution grid considered is  
177 around 1.5 km -length and presents a lifespan of 30 years.

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

185 <**Figure 1** around here>

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

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

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

212 Scenario 4 (Sc4) is based on the valorisation of forest residues derived from traditional poplar stands  
213 which are mainly dedicated to the production of roundwood for pulpwood and furniture production.  
214 Wood residues are managed in the same way as in Sc1, being chipped in the power plant before their  
215 combustion in the CHP unit. All forest operations carried out in the stands have been computed within  
216 the foreground system boundaries (see **Figure 1c**). Thus, organic fertilisation, ploughing, harrowing  
217 and planting have been considered as part of field preparation activities. Herbicide and pest control,  
218 mechanical weed control, irrigation (if necessary depending on the climatic conditions) and harvesting  
219 at the end of the lifespan (12 years) have been included in stand management and harvesting stage.  
220 Finally, field recovery after the harvesting is also performed with an forestry shredder. In this scenario,  
221 economic allocation has been assumed to share out the environmental burdens derived from forest  
222 activities between both co-products (roundwood, 55 €/t and wood residues 4.5 €/t) (Lovarelli et al.,  
223 2018). The rationale behind this approach is the market interest on both co-products.

224 Within each scenario, avoided processes have also been accounted since it is assumed that biomass  
225 combustion allows savings of natural gas for heat production. Therefore, the production of the amount

226 of heat sent for final use in the surroundings (hospital and school) considering the combustion of  
227 natural gas in a domestic boiler has been contemplated

228

## 229 **2.4 Hypotheses and Life cycle inventory**

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

237

<**Table 1** around here>

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

242

<**Table 2** around here>

243 Regarding the production of the feedstocks, forestry residues production (Sc1) has been excluded from  
244 the system boundaries due to the allocation of all environmental burdens derived from forestry  
245 management to the roundwood (main product). Regarding VSRF poplar and willow biomass  
246 production (Sc2 and Sc3, respectively), inventory data regarding forest activities performed in the  
247 stands have been taken from González-García et al. (2012) and Bacenetti et al.(2016), respectively. In  
248 the case of traditional poplar stands, their management has been included within the system  
249 boundaries of Sc4. The following inventory data have been accounted for: the amount of machinery  
250 needed for each specific forest process (tractors and forest equipment), fuel consumption (and  
251 production) in all forest activities (considering operating rate and diesel consumption) as well as the  
252 production of all the agro-chemical inputs to the field, such as herbicides (glyphosate and  
253 gluphosinate-ammonium) and pesticide (Deltamethrin). Regarding fertilisation, it is performed using

254 cattle manure considered as a waste in farming activities. Therefore, impacts from background  
255 activities involved in the production of this organic fertiliser have been excluded from the system  
256 boundaries. Derived emissions from organic fertiliser and agro-chemicals application have been  
257 quantified as well as combustion emissions from diesel use in the machinery. A summary of main  
258 inventory data corresponding to traditional poplar stands is reported in **Table 3**.

259 <**Table 3** around here>

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

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

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

277 <**Table 4** around here>

278  
279 Indirect emissions generated from all the different processes involved have been also included. In this  
280 sense, combustion emission factors corresponding to the biomass burning in the power plant have

281 been taken from the IPCC guidelines (IPCC, 2007) and EMEP/EEA air pollutant emission inventory  
282 guidebook (EMEP/EEA, 2013).

283

## 284 **2.5. Life Cycle Impact Assessment method**

285 Among the steps defined within the life cycle impact assessment stage of the standardised LCA  
286 methodology, only classification and characterisation stages were undertaken (ISO 14040, 2006). The  
287 characterisation factors reported by the ReCiPe Midpoint (H) 1.12 method (Goedkoop et al. 2013a)  
288 were considered to estimate the environmental impacts in this study. According to LCA experts, this  
289 method is the most updated alternative that provides a common framework in which both midpoint  
290 and endpoint indicators can be used, as opposed to similar methodologies to date (PRé Consultants  
291 2017)The implementation of the Life Cycle Inventory data has been performed in the SimaPro v8.2  
292 (PRé Consultants, 2017) software (Goedkoop et al., 2013b). The following impact categories were  
293 selected to evaluate the environmental profile of the different scenarios: climate change (CC),  
294 terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human  
295 toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF) and fossil  
296 depletion (FD). The choice of these impact categories for the environmental study is based on the fact  
297 that they are the most common categories reported in LCA studies of bioenergy systems (Cespi et al.,  
298 2014; Lijó et al., 2017).

299

## 300 **3. Environmental results and discussion**

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

304 <Table 5 around here>

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

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

315 <Figure 2 around here>

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

324 <Figure 3 around here>

325

### 326 **3.1. Assessment per impact category**

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

337 than 85% of total GHG emissions derived from this unit. In Sc2, Sc3 and Sc4, emissions from diesel  
338 combustion in forest machinery are behind the contributions from feedstock production in this impact  
339 category.

340 *TA*: Once again the CHP unit is the key factor responsible for the substances that contribute to this  
341 impact category. In this category, not only the production of electricity requirements is remarkable but  
342 also the emissions produced from diesel combustion in internal machines used in the power plant.  
343 Their contributing ratios add up to 29% and 69% of total effect from CHP unit. Forestry activities  
344 involved in the production of poplar and willow biomass (Sc2 and Sc3) are responsible for 57% and  
345 48% of acidifying substances produced all over the life cycle, respectively. Emissions from diesel use  
346 in forest machines as well as diffuse emissions derived from manure and mineral fertiliser application  
347 dominate the acidifying emissions from that stage.

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

355 *ME*: Scenarios based on the use of biomass from dedicated crops, i.e., poplar and willow respectively  
356 for Sc2 and Sc3, report the worse profile in terms of this impact category being up to 10 and 7 times  
357 higher than Sc1. The rationale behind these results is the production of feedstock (see **Figure 3**).  
358 According to the cultivation description, stands are managed under very short rotation regime  
359 involving numerous fertilisation activities. Cattle manure together with urea are applied in both crops  
360 according to González-García et al. (2012) and Bacenetti et al.(2016).. Thus, diffuse emissions from  
361 fertilising dominate the contributions to this category mainly due to NH<sub>3</sub> emission derived from  
362 nutrient application. In a minor extent, NO<sub>x</sub> emissions derived from diesel combustion in the  
363 agricultural machines also are responsible substances. Regarding Sc4, the profile is lower than Sc2 and  
364 Sc3 being also the feedstock production related activities the main hotspot. However, the cultivation

365 under low intensive conditions and the considered allocation approach (only residues are managed) are  
366 responsible of the best result. In the case of Sc1, activities involved in the power plant constitute the  
367 key factor (~80% of total contributing substances). Direct N-based emissions derived from the  
368 combustion of the biomass in the boiler are the hotspot being responsible of 82% of contributions from  
369 CHP plant.

370 *HT*: As depicted in Figure 3, scenario focused on bio-energy production from forestry residues (Sc1)  
371 reports the worse profile being Sc2, Sc3 and Sc4 around 59%, 64% and 77% smaller than Sc1. The  
372 rationale behind these results is associated with transport activities of the feedstock and derived  
373 emissions from background processes involved. The distribution of feedstock by diesel lorry up to the  
374 power plant gate is the key issue in Sc1 responsible for 67% of contributing substances. In the remaining  
375 scenarios, activities carried out in the CHP plant can be considered as hotspot with contributing ratios  
376 of 57%, 61% and 80%. Emissions from the biomass combustion in the boiler (such as heavy metals  
377 and nitrogen oxides) are behind the power plant effect.

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

387 *FD*: This impact categories represents the consumption of fossil resources all over the life cycle.  
388 Transport activities is the hotspot in Sc1 which could be expected due to the large delivery distance  
389 (800 km), being negligible in the remaining scenarios. Diesel requirements in agricultural activities in  
390 the hotspot in Sc2 and Sc3. Numerous large machines are involved in the cultivation of VSRF poplar  
391 and willow being harvesting and chipping on field (combine harvester) the main responsible ones.

392

### 393 3.2. Comparative assessment between scenarios

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

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

411 Finally, normalisation factors established by ReCiPe Midpoint (H) 1.12 method (Goedkoop et al.  
412 2013a) have been considered in order to obtain an index per scenario and to perform a direct  
413 comparison between scenarios. **Figure 4** depicts the comparative profiles. According to it, the indexes  
414 show that shifting from fossil fuels based energy by renewable one can be or not more environmental  
415 friendly and an specific analysis is mandatory due to the influence of assumptions and bio-energy  
416 system characteristics. The use of dedicated crops (Sc2 and Sc3) contribute to increase the  
417 environmental index as well as the biomass distribution from large distances (Sc1) even though  
418 residues were managed. However and although the use of wood residues for power and heat  
419 production is interesting from environmental and energy perspectives, further analysis should be  
420 focused on the availability of these sources and their ability to meet energy requirements. The results

421 reported in this study support the idea - as also reported in other studies (Caserini et al., 2010; Cespi et  
422 al., 2014; González-García et al., 2014) that the use of agricultural and forest residues could provide a  
423 potential available raw material for bio-energy production. However, more research and technological  
424 development is required to promote their use. Moreover, dedicated crops are interesting due to their  
425 high production yields, guaranteed availability and added benefits such as contributions to rural  
426 development, landscape diversity and reduced erosion potential (Heller et al., 2004). However, more  
427 exploration is necessary to reduce the impacts derived from background processes involved in  
428 agricultural activities (Bacenetti et al., 2018).

429 <Figure 4 around here>

430

### 431 **3.3. Alternative scenarios**

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

445 <Figure 5 around here>

446

### 447 **3.4. Transport effect**

448 The effect of feedstock distribution activities have been remarkable in Sc1 where around 800 km have  
449 been assumed as transport distance. It is a reality since forest stands are widespread in Southern Italy.  
450 However, the influence of transport distance on LCA results has just been considered in previous  
451 studies where power production was environmentally analysed (Nussbaumer and Oser, 2004; Caserini  
452 et al., 2010). In these studies, it was reported that large transport distances imply a high consumption  
453 of primary energy, which could be higher than energy produced.

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

463 <Figure 6 around here>

464

465

#### 466 **4. Conclusions and future outlook**

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

474 The current efforts performed in recent years have given rise to numerous technological developments  
475 enhancing “closing the loop” strategies under a biorefinery concept through better recycling and re-

476 using the waste streams. Wood-based residues availability and low associated costs in comparison  
477 with dedicated bio-energy crops support also their interest.

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

486

#### 487 **Acknowledgements**

488 This research has been partially supported by a project granted by Xunta de Galicia (project ref.  
489 ED431F 2016/001) and by the STAR-ProBio project funded by the European Union's Horizon 2020  
490 Program research and innovation programme under grant agreement No. 727740.

491 S.G-G. would like to express their gratitude to the Spanish Ministry of Economy and Competitiveness  
492 for financial support (Grant references RYC-2014-14984). S.G-G. belongs to the Galician Competitive  
493 Research Group GRC 2013-032 and to CRETUS Strategic Partnership (AGRUP2015/02). All these  
494 programmes are co-funded by Xunta de Galicia and FEDER (EU).

495 Authors give thanks to the European Commission, through the Erasmus+Call 2017-KA1-Mobility of  
496 staff in higher education-Staff mobility for teaching and training activities.

497

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