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

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15   **Abstract**

16   The concerns related to the environmental impact related to energy production from fossil fuel are

17   increasing. In this context, the substitution of fossil fuel based energy by bio-energy can be an

18   effective solution. In this study, the production of electricity and heat in Italy in a combined heat and

19   power plant (CHP) based on an Organic Rankine Cycle (ORC) turbine from wood based biomass both

20   from forest and agricultural activities has been analysed considering four potential alternative

21   scenarios to the current energy status: biomass from very short rotation forestry (VSRF) poplar and

22   willow stands as well as residues from natural forests and from traditional poplar plantations. The

23   evaluation has been performed by applying Life Cycle Assessment (LCA) method and an attributional

24   cradle-to-gate approach has been followed. The expected savings of greenhouse gases emission and

25   fossil fuels demand have been quantified, as well as derived emissions of toxic pollutants and

26   substances responsible for acidification, eutrophication and photochemical oxidant formation.The

27   results have been also compared with the conventional Italian scenario considering the current Italian

28   electricity profile and heat production from natural gas. Among the different scenarios, due to the

29 lower transport distance, the use of biomass from traditional poplar plantation residues shows the

30 lowest impact. The biomass combustion emissions are the main hotspot for several evaluated impact

31 categories (e.g., particulate matter formation, human toxicity). In fact, when the produced bio-energy

32 is compared to the reference system (i.e., electricity produced under the Italian electric profile) the

33 results do not favor bio-energy systems. The results reported in this study support the idea that forest

34 residues would be an interesting and potential feedstock for bio-energy purposes although further

35 research is required specifically with the aim of optimizing biomass supply distances.

36

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

38 Willow

39

1. Introduction

40

41 Mitigation of climate change and derived effects is a global challenge (IPCC, 2007) motivating the

42 international community to introduce easing strategies (Oreggioni et al., 2017). Therefore, European

43 Union's energy and climate change plans try to avoid the use of fossil-based energy by means of the

44 promotion of bio-energy (Directive 2009/28/EC; European Commission, 2018). In this sense, energy

45 industries have contributed to ~32% of global CO_2 emission over the last 20 years (Janssens-

46 Maenhout et al., 2012; Oreggioni et al., 2017) as well as heating and cooling processes are

47 responsible for approximately 50% of the final European energy demand (Tsupari et al., 2017). Finally

48 it is important to note that, in Europe, fuel combustion in energy industries is the most important

49 contributor to anthropogenic climate change, with 28.5% of total greenhouse gases (GHG) emissions

50 in 2015 (Eurostat, 2018).

51 Bio-energy is a critical issue for multiple reasons besides environmental concerns such as i) to

52 guarantee energy security through a more diversified energy mix and less reliance on imported fossil-

53 energy carriers, ii) the sustainable use of natural resources as well as iii) the need to revitalize rural

54 economies (Buonocore et al., 2012; Börjesson Hagberg et al., 2016). Thus, an increased share of

55 renewable energy is mandatory in energy system to satisfy the mentioned issues besides reducing

56 greenhouse gases (GHG) emission. In addition, improvements in power plant efficiency and the

57 incorporation of carbon capture and storage (CCS) processes are also required, receiving the latter

58 special attention in recent years (Tsupari et al., 2017).

59 Bio-energy systems include a full range of products such as bio-ethanol, bio-diesel, biogas, electricity

60 and heat, all of them from a large range of potential feedstocks – e.g., wood from forests, crops,

61 seaweed and animal, forest and agricultural wastes (González-García et al., 2014). Moreover, biomass

62 as its primary product is a versatile energy source that can be stored and converted to energy on-

63 demand (De Meyer et al., 2014). The waste-to-energy concept is being highly promoted as a part of

64 the efforts into sustainable development in energy sector (Ferreira et al., 2017). The use of forest and

65 agricultural residues as well as other biomass waste from agricultural and industrial activities for bio-

66 energy production (mainly electricity and heat) plays a key role in the energy system (Eurostat, 2015)

67 and it is expected to increase over the next few years. According to MISE (2012), the share of energy

68   from renewable energy sources should reach in 2020 the 17% of the total national energy

69   consumption. In this sense, there is a clear potential for increased use of wood for energy purposes in

70   the EU, mostly related to forest residues and complementary fellings (SFC-WGII, 2008).

71   However, discrepancies also exist regarding bio-energy supply from biomass mostly due to the high

72   cost associated to the production of biomass-based electricity (Cleary and Caspersen, 2015b).

73   Therefore, to beat this economic barrier, many governments offer subsidies to encourage investment in

74   bio-energy technologies. Bio-energy production costs, outside of the cost of feedstock production,

75   tend to decrease with scale (Cameron et al., 2007; Dornburg and Faaij, 2001). Thus, supply-side

76   funding programs frequently provide greater economic support for smaller-scale projects within a

77   given technology class. However, the discontinuous availability and the relatively high maintenance

78   and logistic costs hinder the economic convenience of biomass for large scale energy production (De

79   Meyer et al., 2014). Therefore, numerous efforts are being carried out to make the whole process

80   achievable from an economic approach (De Meyer et al., 2014)

81   Production of heat and electricity from woody residues either from forest or agricultural activities

82   could considerably increase the contribution to energy security, reduce GHG emission and add value

83   to waste materials (Matsumura et al., 2005; Fernandes and Costa, 2010; Aldana et al., 2014). Indeed, it

84   is a common practice in factories such as pulp mills where pulp is generated together with heat and

85   electricity (Sandin et al., 2015). Different studies evaluated the potential quantities of available forest

86   biomass residues for energy production in countries such as Portugal (Fernandes and Costa, 2010;

87   Viana et al., 2010; Lourinho and Brito, 2015) or Uganda (Okello et al., 2013). According to them, only

88   if cogeneration is implemented the wood fuel resource should be sufficient to satisfay the required

89   capacity demand. However, special attention must be paid into the biomass-supply competition with

90   pellets production, one of the largest internationally traded solid biomass commodities for energy

91   purposes mainly derived from wood residues (Sikkema et al., 2011; Monteiro et al., 2012).

92   Italy's energy profile relies to a very large extent on imports to meet its energy needs since Italian

93   energy reserves are scarce. In this sense, Italy is a net importer of electricity and only 88.2% of

94   demand is satisfied by a national production. Regarding its power production capacity, 15.3%

95   corresponds to hydropower and 15.9% derives from renewable sources, and the remaining is produced

96   from fossil sources (Terna, 2016).

97   Hence, its interest on promoting a sharp increase on power production from renewable sources, being

98   Italy considered one of the European countries (together with France, Germany, Sweden, Finland,

99   Spain and United Kingdom) with the main bioenergy markets in 2020 (Calcante et al., 2018; Scarlat et

100   al., 2013).

101   Poplar and willow are short rotation coppice-species most cultivated in Italy, specially in Po Valley

102   (Northern Italy), for bio-energy and industrial (e.g., pulpwood and paper) purposes (González-García

103   et al, 2012; Bacenetti et al., 2016). Poplar and willow cultivation (either at short rotation or very short

104   rotation forestry regimes, SRF and VSRF respectively) includes activities such as harvesting and

105   biomass collection, which are repeated in different times depending on the cultivation regime. Both

106   activities involve the production of leaves and stools that, usually, remains in the plantation as nutrient

107   and carbon supplier (González-García et al., 2012). Nevertheless, they could be used for bio-energy

108   applications (Muth et al., 2013).

109   Traditional poplar plantation also exists in Italy mainly in Po Valley mostly destined to roundwood

110   production for furniture sector (Verani et al., 2017). It involves a non-intensive management regime

111   involving the production of potential woody biomass with only one harvesting event as difference to

112   SRF and VSRF regimes.

113   In the case of Italy, forests are widespread in all the regions of the country being destined to firewood

114   and roundwood production (Proto et al., 2017). Forestry with 10,467,000 ha cover about 34.7% of

115   Italy (INFC, 2015). Although a variety of management systems exist for forests, shelter cut (high

116   forest) in combination with natural regeneration is widespread. In this case, woody residues (mainly

117   tops and brances), produced during logging operations, can be used for bio-energy applications.

118   In this study, the production of electricity and heat in Italy from wood based biomass either from

119   forest and from agricultural activities has been analysed considering different production scenarios and

120   final uses. The interest behind this study is the promoting use of biomass in small combustion

121   installations in Italy as substitute for fossil fuels (Benetto et al., 2004; Caserini et al., 2010). Biomass

122   from VSRF poplar and willow stands as well as residues from natural forests and from traditional

123 poplar plantations have been considered for analysis. Attention has been paid on dedicated energy

124 crops (i.e., willow and poplar) due to the current Italian interest on biomass power plants.

125 The results have been also compared with the conventional Italian scenario considering the current

126 Italian electricity profile and heat production from natural gas. The assessment has been performed by

127 applying Life Cycle Assessment (LCA) methodology in an attributional approach and a cradle-to-

128 power plant gate perspective. A comprehensive and transparent analysis has been performed to

129 facilitate comparisons between the proposed bio-energy scenarios.

130

131 **2. Materials and methods**

132 Life Cycle Assessment (LCA) is a widely used and standardised tool for the systematic evaluation of

133 environmental aspects of a production system through all stages of its life cycle (ISO 14040, 2006). It

134 is considered an ideal instrument to evaluate the environmental dimension of sustainability. Numerous

135 studies related to bio-energy production have been also used this methodology to assess their

136 environmental consequences (Benetto et al., 2004; Keoleian and Volk, 2005; Caserini et al., 2010;

137 Cherubini and Strømman, 2011; González-García et al., 2014; Asdrubali et al., 2015; Patel et al.,

138 2016). Within these studies, special attention was paid into liquid fuels production being the number

139 of published studies focused on heat and power generation slightly lower (Cherubini and Strømman,

140 2011). However, its applicability in this area has been entirely demonstrated.

141

142 **2.1. Goal and scope definition**

143 This study aims to assess and compare the environmental consequences and energy requirements

144 associated with the production of bio-energy (heat and power) for district heating systems and national

145 grid suply from different biomass sources including energy crops derived from VSRF and forest

146 residues. Biomass combustion is the simplest thermochemical conversion technology being heat and

147 power (under co-generation regime) the main co-products of direct combustion of lignocellulosic

148 material (Patel et al., 2016). Thus, different scenarios have been proposed for assessment trying to

149 identify hotspots and differences.

150   In addition and as reference system for the comparison of the results, the production of heat

151   considering a fossil source (i.e., natural gas) in a domestic boiler in the domestic sector as well as

152   electricity production in the Italian national grid have been considered within the analysis to be

153   compared with the designed scenarios proposed for analysis. The rationale behind this consideration is

154   that the bio-energy modelled scenarios allow saving of both fossil based production routes.

155

156   **2.2. Functional unit**

157   The functional unit considered to report the environmental profile is 1 kWh of electricity (kWhe)

158   produced in a combined heat and power plant (CHP) based on an Organic Rankine Cycle (ORC) and

159   with an energy efficiency of 20% in the ORC and 85% in the boiler, regardless the biomass source.

160   The consideration of an energy-based functional unit has also been considered in previous LCA

161   studies available in the literature (González-García et al. 2014) allowing the comparison with

162   alternative production systems with independence of the feedstock used (Muench and Guenther,

163   2013).

164

165   **2.3. System boundaries definition**

166   An attributional cradle-to-gate approach has been followed in this study in all the scenarios proposed

167   for analysis i.e., from raw materials extraction till the production of energy in the plant. Thus, the

168   further use of the produced electricity has been excluded from analysis. The CHP is mainly constituted

169   by two different sections. The first one is characterised by a biomass boiler (thermal power of 6.047

170   MW) fed with the woody biomass while the second section is mainly constituted by a ORC turbine

171   with 1 MW of electric power. The Organic Rankine Cycle's principle is based on a turbogenerator

172   working as a conventional steam turbine to transform thermal energy into mechanical energy and

173   finally into electric energy. Instead of generating steam from water, the ORC system vaporises an

174   organic fluid, characterised by a molecular mass higher than that of water (e.g., HCFC-123 with a

175   molecular weitght of $152.9 \text{g} \cdot \text{mol}^{-1}$), which leads to a slower rotation of the turbine, lower pressures

176   and no erosion of the metal parts and blades.

177   At the CHP plant, the heat produced by the biomass boiler is transferred, using a diathermic oil (310-

178   315 °C and 6 bar), to the ORC where is transformed in mechanical power and, through a electrical

179   generator, in electricity. More in details, the organic fluid vapor rotates the turbine, which is directly

180   coupled to the electric generator. Afther that, the exhaust vapor flows through the regenerator, where it

181   is then condensed in the condenser and cooled by the cooling circuit. The thermal energy used in the

182   district heating is recovered at the condenser. The district heating distribution grid considered is

183   around 1.5 km -length and presents a lifespan of 30 years.

184   **Figure 1** displays the foreground system boundaries corresponding to the four scenarios considered as

185   base case studies. All electricity produced is directly fed into the Italian national grid. There is no

186   recycling to satisfy electricity demand in the CHP unit due to technical reasons (the different electric

187   devices for biomass loading, exhaust gas treatment, ash removal etc. must operate also when the ORC

188   does not work for maintenance or breakages) (Fiala, 2012). Regarding heat, only the 16% of all heat

189   produced in sent to a nearby hospital and school to satisfy heating requirements. The remaining 84%

190   is considered as a waste since it is not recovered.

191   <**Figure 1** around here>

192   Scenario 1 (Sc1) is based on the consideration of residues from natural regeneration forestry and

193   industrial activities as feedstock. These stands are naturally managed i.e., they are handled under low

194   management intesity. The forest stands are untouched forests with a history of limited management

195   (Buiteveld et al., 2007). Thus, no activities are performed throughout the lifespan (> 60 years) after

196   initially diversifying the forest structure (Buiteveld et al., 2007). Biomass extracted is mostly

197   dedicated as raw material (roundwood) for furniture sector. Wood residues such as tops and branches

198   are recovered in the harvesting activities as well as throughout the lifespan of the plantation. In this

199   scenario, these residues are considered as raw material for bio-energy production (see **Figure 1a**).

200   Firstly, wood residues are chipped into the forestry using a self-propelled chipper and after they are

201   transported to the bio-energy plant. Residues from furniture production activities are also considered

202   and chipped in the plant. In this scenario, the entire environmental burdens of the multifunctional

203   process (only derived from logging operations) are allocated to the main product (roundwood).

204   Therefore, wood residues are considered waste and free of environmental burdens except with regard

205   to forest residues chipping and chip wood transport. This approach is sometimes deemed reasonable

206   specially if the demand of the co-products has no influence on te production capacity of the system

207   (Sandin et al., 2015).

208   Scenario 2 (Sc2) and Scenario 3 (Sc3) consider the biomass from VSRF stands of poplar and willow

209   species, respectively, as feedstock for heat and power generation (see **Figure 1b**). The management of

210   VSRF plantations has been considered within the system boundaries considering all processes

211   performed in the stands from field preparation and management, harvesting and field recovery at the

212   end of the lifespan of the plantations (approximately ten years in both species) in agreement with

213   González-García et al. (2012) and Bacenetti et al. (2016). It is important to highlight that as difference

214   to forest stands dedicated to roundwood production for industrial uses, all the produced biomass

215   (including wood residues such as branches, stools and leaves) is recovered and sent to bio-energy

216   production. The total trees are felled, and directly chipped on the field by means of a forage harvesters

217   equipped for a specific header.

218   Scenario 4 (Sc4) is based on the valorisation of forest residues derived from traditional poplar stands

219   which are mainly dedicated to the production of roundwood for pulpuwod and furniture production.

220   Wood residues are managed in the same way as in Sc1, being chipped in the power plant before their

221   combustion in the CHP unit. All forest operations carried out in the stands have been computed within

222   the foreground system boundaries (see **Figure 1c**). Thus, organic fertilisation, ploughing, harrowing

223   and planting have been considered as part of field preparation activities. Herbicide and pest control,

224   mechanical weed control, irrigation (if necessary depending on the climatic conditions) and harvesting

225   at the end of the lifespan (12 years) have been included in stand management and harvesting stage.

226   Finally, field recovery after the harvesting is also performed with an forestry shredder. In this scenario,

227   economic allocation has been assumed to share out the environmental burdens derived from forest

228   activities between both co-products (roundwood, 55 €/t and wood residues 4.5 €/t) (Lovarelli et al.,

229   2018). The rationale behind this approach is the market interest on both co-products.

230   Within each scenario, avoided processes have also been accounted since it is assumed that biomass

231   combustion allows savings of natural gas for heat production. Therefore, the production of the amount

232 of heat sent for final use in the surroundings (hospital and school) considering the combustion of

233 natural gas in a domestic boiler has been contemplated

234

235 **2.4 Hypotheses and Life cycle inventory**

236 A reliable environmental assessment requires the collection of high quality inventory data. The

237 biomass conversion process into heat and power present a wide range of material and energy

238 exchanges with the technosphere and the environment. Thus, masss and energy flows need to be

239 estimated as well as avoided impacts related to the processes involved in each scenario. Therefore, the

240 mass and energy flows corresponding to the foreground systems (**Figure 1**) have been modelled and

241 quantified for each type of feedstock. A summary of the most relevant inventory data per scenario is

242 reported in **Table 1**.

243 <**Table 1** around here>

244 The estimation of the amounts of biomass necessary to produce 1 1 kWhe (functional unit) has

245 followed the method defined by Butnar et al. (2010) based on the power plant capacity, the operation

246 hours, the efficiency, the low heating value (LHV) and moisture content for each biomass source

247 (**Table 2**).

248 <**Table 2** around here>

249 Regarding the production of the feedstocks, forestry residues production (Sc1) has been excluded from

250 the system boundaries due to the allocation of all environmental burdens derived from forestry

251 management to the roundwood (main product). Regarding VSRF poplar and willow biomass

252 production (Sc2 and Sc3, respectively), inventory data regarding forest activities performed in the

253 stands have been taken from González-García et al. (2012) and Bacenetti et al.(2016), respectively. In

254 the case of traditional poplar stands, their management has been included within the system

255 boundaries of Sc4. The following inventory data have been accounded for: the amount of machinery

256 needed for each specific forest process (tractors and forest equipment), fuel consumption (and

257 production) in all forest activities (considering operating rate and diesel consumption) as well as the

258 production of all the agro-chemical inputs to the field, such as herbicides (glyphosate and

259 gluphosinate-ammonium) and pesticide (Deltamethrin). Regarding fertilisation, it is performed using

260 cattle manure considered as a waste in farming activities. Therefore, impacts from background

261 activities involved in the production of this organic fertiliser have been excluded from the system

262 boundaries. Derived emissions from organic fertiliser and agro-chemicals application have been

263 quantified as well as combustion emissions from diesel use in the machinery. A summary of main

264 inventory data corresponding to traditional poplar stands is reported in **Table 3**.

265   <**Table 3** around here>

266 Concerning the biomass supply till the power plant, it has been computed in the analysis. In all the

267 scenarios it has been assumed that the power plant is placed within the Lombardy region. This region

268 has gained relevance in the last years due to the establishment of several biomass thermoelectric

269 power plants (Bergante et al., 2010; Lijó et al., 2017). Forestry wood residues are transported by

270 lorries (16-32 t) an average distance of 800 km (from forestry located in Southern Italy). Poplar and

271 willow plantations are extended around the Po Valley (Lombardy region). Thus, an average transport

272 distance of 35 km by lorry (16-32 t) has been assumed in both cases. In the case of wood residues

273 from traditional poplar stands, 20 km has been considered. Diesel lorries have been used for biomass

274 transport in all the scenarios.

275 Although primary data should be used whenever possible, it is sometimes necessary to turn to

276 secondary ones. In this study, information regarding the diesel consumed in the chipping process (Sc1

277 and Sc4), electricity required in the CHP unit (all scenarios) as well as ashes disposal in a sanitary

278 landfill, has been taken from the Ecoinvent ® database (Weidema et al., 2013).

279 Moreover, inventory data corresponding to the background system, which involves the production of

280 utilities (electricity), other inputs to the foreground system (agro-chemicals, water, machinery) and

281 infrastructure (e.g., the distribution grid) have been taken from a pre-existing database and the

282 literature as detailed in **Table 4**.

283   <**Table 4** around here>

284

285 Indirect emissions generated from all the different processes involved have been also included. In this

286 sense, combustion emission factors corresponding to the biomass burning in the power plant have

287   been taken from the IPCC guidelines (IPCC, 2007) and EMEP/EEA air pollutant emission inventory

288   guidebook (EMEP/EEA, 2013).

289

290   **2.5. Life Cycle Impact Assessment method**

291   Among the steps defined within the life cycle impact assessment stage of the standardised LCA

292   methodology, only classification and characterisation stages were undertaken (ISO 14040, 2006). The

293   characterisation factors reported by the ReCiPe Midpoint (H) 1.12 method (Goedkoop et al. 2013a)

294   were considered to estimate the environmental impacts in this study. According to LCA experts, this

295   method is the most updated alternative that provides a common framework in which both midpoint

296   and endpoint indicators can be used, as opposed to similar methodologies to date (PRé Consultants

297   2017)The implementation of the Life Cycle Inventory data has been performed in the SimaPro v8.2

298   (PRé Consultants, 2017) software (Goedkoop et al., 2013b). The following impact categories were

299   selected to evaluate the environmental profile of the different scenarios: climate change (CC),

300   terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human

301   toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF) and fossil

302   depletion (FD). The choice of these impact categories for the environmental study is based on the fact

303   that they are the most common categories reported in LCA studies of bioenergy systems (Cespi et al.,

304   2014; Lijó et al., 2017).

305

306   **3. Environmental results and discussion**

307   The scenarios proposed for assessment have been analysed from an environmental perspective in order

308   to identify their hotspots as well as to compare their profiles with the aim of identifying differences.

309   The characterisation results are detailed in **Table 5**.

310   <**Table 5** around here>

311   **Figure 2** displays the comparative profiles between the scenarios under assessment and the reference

312   system (i.e., electricity production under the Italian electric profile). According to the results, all of the

313   evaluated bio-energy scenarios involve environmental beneftis in terms of impact categories such as

314   CC and FD. According to previous studies, the substitution of fossil fuels with biomass sources to

315   produce energy requirements implies a saving of GHG emission as well as fossil fuels depletion

316   (Caserini et al., 2010; González-García et al., 2014). Although a detailed analysis per scenario is

317   reported below, the rationale behind these environmental benefits is linked to the avoided process

318   included within the system boundaries. Regardless the scenario, electricity produced together with

319   heat subsequently used (~16%) involve the avoidance of producing it from conventional way that is,

320   from the combustion of natural gas in an domestic boiler.

321   <**Figure 2** around here>

322   A discussion for each impact category is presented in the following sections. **Figure 3** depicts the

323   main activities or processes for each impact category analysed and bio-energy scenario, as resulting

324   from the contributions analysis. It is important to note that the amount of heat and electricity produced

325   in all scenarios is exactly the same (see **Table 1**). Therefore, the contribution from the avoided process

326   is also the same in terms of characterisation results. Thus, differences on the profiles are directly

327   linked to the differences on the foreground system. Positive values in **Figure 3** are indicative of

328   environmental burdens, whereas negative values are indicative of environmental credits/benefits

329   derived from avoided process.

330   <**Figure 3** around here>

331

332   **3.1. Assessment per impact category**

333   *CC*: In this impact category the CHP unit is considered as an environmental hotspot regardless the

334   scenario under study. Although in Sc1, it is really important the effect of transport activities from

335   forest site till the power plant, which could be expected due to the large transport distance (800 km).

336   The contributions in the remaining scenarios from this process are not remarkable. However, attention

337   should be paid to the feedstock production in Sc2 and Sc3 (and in Sc4 in a minor extent). In both

338   cases, the biomass is specifically produced for bio-energy purposes under a VSRF regime involving

339   numerous forestry activities and diesel requirements. In Sc4, poplar biomass is produced under a

340   traditional regime, less intensive than in the other two and biomass is cultivated with other uses (e.g.

341   furniture) being only the residues considered for bio-energy purposes. Production of electricity

342   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

371   under low intensive conditions and the considered allocation approach (only residues are managed) are

372   responsible of the best result. In the case of Sc1, activities involved in the power plant constitute the

373   key factor (~80% of total contributing substances). Direct N-based emissions derived from the

374   combustion of the biomass in the boiler are the hotspot being responsible of 82% of contributions from

375   CHP plant.

376   *HT*: As depicted in Figure 3, scenario focused on bio-energy production from forestry residues (Sc1)

377   reports the worse profile being Sc2, Sc3 and Sc4 around 59%, 64% and 77% smaller than Sc1. The

378   rationale behind these results is associated with transport activities of the feedstock and derived

379   emissions from background processes involved. The distribution of feedstock by diesel lorry up to the

380   power plant gate is the key issue in Sc1 responsible for 67% of contributing substances. In the reaming

381   scenarios, activities carried out in the CHP plant can be considered as hotspot with contributing ratios

382   of 57%, 61% and 80%. Emissions from the biomass combustion in the boiler (such as heavy metals

383   and nitrogen oxides) are behind the power plant effect.

384   *POF* and *PMF*: Results in these impact categories are directly related as depicted in Figure 3. POF

385   takes into account the emissions into air of substances (e.g. nitrogen dioxide, nitrogen oxides, sulfur

386   oxides or toluene) that produce photochemical smog. Regarding PMF, it considers the emission of

387   particulates as well as sulfur oxides, nitrogen oxides and ammonia, which can also produce smog.

388   Therefore, the profiles in both impact categories regardless the scenario analysed are almost identical.

389   In all scenarios, emissions from biomass combustion (e.g., of particulates and nitrogen oxides) in the

390   boiler within the power plant can be considered as the hotspot. However, in Sc1 it is also outstanding

391   the effect from biomass distribution. In the case of Sc2 and Sc3, agricultural activities required to the

392   biomass production are remarkable in both impact categories mainly due to the use of diesel machines.

393   *FD*: This impact categories represents the consumption of fossil resources all over the life cycle.

394   Transport activities is the hotspot in Sc1 which could be expected due to the large delivery distance

395   (800 km), being negligible in the remaining scenarios. Diesel requirements in agricultural activities in

396   the hotspot in Sc2 and Sc3. Numerous large machines are involved in the cultivation of VSRF poplar

397   and willow being harvesting and chipping on field (combine harvester) the main responsible ones.

398

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

427 reported in this study support the idea - as also reported in other studies (Caserini et al., 2010; Cespi et

428 al., 2014; González-García et al., 2014) that the use of agricultural and forest residues could provide a

429 potential available raw material for bio-energy production. However, more research and technological

430 development is required to promote their use. Moreover, dedicated crops are interesting due to their

431 high production yields, guaranteed availability and added benefits such as contributions to rural

432 development, landscape diversity and reduced erosion potential (Heller et al., 2004). However, more

433 exploration is necessary to reduce the impacts derived from background processes involved in

434 agricultural activities (Bacenetti et al., 2018).

435 <**Figure 4** around here>

436

437 **3.3. Alternative scenarios**

438 In the scenarios considered for analysis, only 16% of total heat produced in the CHP plant is finally

439 used being the remaining 84% wasted into air. However, it should be interesting the recovery and final

440 use of the total heat produced (e.g., it could be considered in heating systems in the surrounding

441 areas). Thus, 14.11MJ should be produced per kWhe, which should avoid the production of that

442 amount of heat from natural gas. Moreover, electricity requirements in the power plant are directly

443 taken from the national grid. However, it could be feasible to satisfy its electricity requirements (0.24

444 kWhe) recycling it from the electricity produced, being 0.76 kWhe sent to the national grid. The

445 consideration of both hypothesis has been considered for analysis and **Figure 5** displays the

446 comparative profiles between the bio-energy scenarios and the alternative ones considing a normalised

447 index. Taking in mind the results, it is demonstrated the environmental benefits of producing both heat

448 and electricity from wood residues and dedicated crops in comparison with the current national

449 electric profile. In this sense, environmental credits could be achieved mostly using wood residues

450 from tradional poplar stands and willow-based biomass.

451 <**Figure 5** around here>

452

453 **3.4. Transport effect**

454   The effect of feedstock distribution activities have been remarkable in Sc1 where around 800 km have

455   been assumed as transport distance. It is a reality since forest stands are widespread in Southern Italy.

456   However, the influence of transport distance on LCA results has just been considered in previous

457   studies where power production was environmentally analysed (Nussbaumer and Oser, 2004; Caserini

458   et al., 2010). In these studies, it was reported that large transport distances imply a high consumption

459   of primary energy, which could be higher than energy produced.

460   According to INFC (2015), in Italy, forestry are widespread also in the Central Italy (Appennino and,

461   in particular, Tuscany and Umbria regions) as well as in Northern Italy (e.g., Veneto, Trentino).

462   Therefore, a comparative analysis has been performed to identify the benefits of processing forest

463   residues from closer areas. Average transport distances of 300-350 km and 350-370 km have been

464   assumed respectively for forestry residues distribution from Tuscany (ScA) and Northern Italy (ScB).

465   **Figure 6** displays the comparative profiles considering the normalisation score. According to it,

466   outstanding reductions of the environmental profile could be achieved of up to 40% in residues are

467   delivered from Central Italy regions. Thus, transport distance plays a key role on the environmental

468   profiles and could be decisive in decision making strategies.

469   <**Figure 6** around here>

470

471

472   **4. Conclusions and future outlook**

473   The results reported in this study support the idea that wood residues would be an interesting and

474   potential raw material for bio-energy purposes although further research is required either from

475   environmental and economic point of views. Wood residues from natural regerenation forest,

476   industrial activities and traditional poplar stands seem to be favourable to dedicated energy crops in a

477   global approach. Thus, it must be encouraged the use of forest and wood-processing residues as

478   feedstock from a circular economy approach not only in the bio-energy sector but also in the latent

479   bio-based industry.

480   The current efforts performed in recent years have given rise to numerous technological developments

481   enhancing "closing the loop" strategies under a biorefinery concept through better recycling and re-

482 using the waste streams. Wood-based residues availability and low associated costs in comparison

483 with dedicated bio-energy crops support also their interest.

484 According to the main findings from this study, LCA methodology can be considered as a valuable

485 and useful tool to support decision making strategies under an environmental approach, specifically

486 for systems under development such as the ones reported in this study. However, additional research

487 should be perfomed not only in the environmental pillar of the sustainability but also in the social and

488 economic ones to obtain a full overview. Moreover, attention must be paid in these categories different

489 than climate change and fossil depletion (the ones that are subject of great public debate), considerably

490 affected by air pollutant emissions derived from biomass combustion mostly when dedicated energy

491 crops are considered.

492

503

504 **References**

505 Aldana, H., Lozano, F. J., Acevedo, J. (2014). Evaluating the potential for producing energy

506 from agricultural residues in México using MILP optimization. Biomass and Bioenergy, 67, 372-389.

507 Asdrubali, F., Baldinelli, G., D'Alessandro, F., & Scrucca, F. (2015). Life cycle assessment of

508 electricity production from renewable energies: Review and results harmonization. Renewable and

509 Sustainable Energy Reviews, 42, 1113-1122.

510   Bacenetti J., Lovarelli D., Facchinetti D., Pessina D. (2018). An environmental comparison of

511   techniques to reduce pollutants emissions related to agricultural tractors. Biosystems Engineering, 171,

512   30-40

513   Bacenetti, J., Bergante, S., Facciotto, G., Fiala, M. (2016). Woody biofuel production from

514   short rotation coppice in Italy: Environmental-impact assessment of different species and crop

515   management. Biomass and Bioenergy, 94, 209-219.

516   Benetto E, Popocivi EC, Rousseaux P, Blondin J., 2004. Life cycle assessment of fossil CO_2

517   emissions reduction scenarios in coal-biomass based electricity production. Energy Conversion

518   Management, 24, 3053–3074.

519   Bergante, S., Facciotto, G., Minotta, G., 2010. Identification of the main site factors and

520   management intensity affecting the establishment of short-rotationcoppices (SRC) in Northern Italy

521   through stepwise regression analysis. Central European Journal of Biology, 5, 522-530.

522   Bergante, S., Manzone, M., Facciotto, G. (2016). Alternative planting method for short

523   rotation coppice with poplar and willow. Biomass and Bioenergy, 87, 39-45.

524   Buiteveld, J., Vendramin, G. G., Leonardi, S., Kamer, K., Geburek, T. (2007). Genetic

525   diversity and differentiation in European beech (Fagus sylvatica L.) stands varying in management

526   history. Forest ecology and management, 247(1-3), 98-106.

527   Buonocore, E., Franzese, P. P., Ulgiati, S. (2012). Assessing the environmental performance

528   and sustainability of bioenergy production in Sweden: a life cycle assessment perspective. Energy,

529   37(1), 69-78.

530   Calcante, A., Facchinetti, D., Pessina, D. (2018). Analysis of Hazardous Emissions of Hand-

531   Operated Forestry Machines Fuelled with Standard Mix or Alkylate Gasoline. Croatian Journal of

532   Forest Engineering: Journal for Theory and Application of Forestry Engineering, 39(1), 109-116.

533   Calo, F., Moreno, B., Zamorano, M., Szanto, M., 2005. Environmental diagnosis methodology

534   for municiplal waste landfills. Waste Management, 25, 768-779.

535   Cameron, J. B., Kumar, A., Flynn, P. C. (2007). The impact of feedstock cost on technology

536   selection and optimum size. Biomass and Bioenergy, 31(2-3), 137-144.

537   Caserini, S., Livio, S., Giugliano, M., Grosso, M., Rigamonti, L. (2010). LCA of domestic and

538   centralized biomass combustion: the case of Lombardy (Italy). Biomass and Bioenergy, 34(4), 474-

539   482.

540   Cespi, D., Passarini, F., Ciacci, L., Vassura, I., Castellani, V., Collina, E., Morselli, L. (2014).

541   Heating systems LCA: comparison of biomass-based appliances. The International Journal of Life

542   Cycle Assessment, 19(1), 89-99.

543   Cherubini, F., Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: state of

544   the art and future challenges. Bioresource technology, 102(2), 437-451.

545   Cleary, J., Caspersen, J. P. (2015). Comparing the life cycle impacts of using harvest residue

546   as feedstock for small-and large-scale bioenergy systems (part I). Energy, 88, 917-926.

547   Cleary, J., Wolf, D. P., Caspersen, J. P. (2015). Comparing the life cycle costs of using harvest

548   residue as feedstock for small-and large-scale bioenergy systems (part II). Energy, 86, 539-547.

549   De Meyer, A., Cattrysse, D., Rasinmäki, J., Van Orshoven, J. (2014). Methods to optimise the

550   design and management of biomass-for-bioenergy supply chains: A review. Renewable and

551   sustainable energy reviews, 31, 657-670.

552   Directive 2009/28/EC, 2009. Directive 2009/28/EC of the European Parliament and of the

553   Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending

554   and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union. L140/16-62

555   Djomo, S. N., Ac, A., Zenone, T., De Groote, T., Bergante, S., Facciotto, G., Ceulemans, R.

556   (2015). Energy performances of intensive and extensive short rotation cropping systems for woody

557   biomass production in the EU. Renewable and Sustainable Energy Reviews, 41, 845-854.

558   Dornburg, V., Faaij, A. P. (2001). Efficiency and economy of wood-fired biomass energy

559   systems in relation to scale regarding heat and power generation using combustion and gasification

560   technologies. Biomass and Bioenergy, 21(2), 91-108.

561   Eurostat, 2015. SHARES 2015 - Short Assessment of Renewable Energy Sources

562   Eurostat,   2018.   http://ec.europa.eu/eurostat/statistics-

563   explained/index.php/Europe_2020_indicators_-_climate_change_and_energy (accessed 23 April,

564   2018)

565   Fernandes, U., Costa, M. (2010). Potential of biomass residues for energy production and

566   utilization in a region of Portugal. Biomass and Bioenergy, 34(5), 661-666.

567   Ferreira, S., Monteiro, E., Brito, P., Vilarinho, C. (2017). Biomass resources in Portugal:

568   Current status and prospects. Renewable and Sustainable Energy Reviews, 78, 1221-1235.

569   Fiala, M., 2012. Energia da biomasse, Maggioli Editore. 1 – 437.

570   Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J. van Zelm R (2013a).

571   ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators

572   at the midpoint and the endpoint level. Report I: Characterisation. 1st ed. (version 1.08)

573   Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2013b. Introduction to LCA

574   with SimaPro 8. PRé Consultants. The Netherlands

575   González-García, S., Bacenetti, J., Murphy, R. J., Fiala, M. (2012). Present and future

576   environmental impact of poplar cultivation in the Po Valley (Italy) under different crop management

577   systems. Journal of cleaner production, 26, 56-66.

578   González-García, S., Dias, A. C., Clermidy, S., Benoist, A., Maurel, V. B., Gasol, C. M.,

579   Arroja, L. (2014). Comparative environmental and energy profiles of potential bioenergy production

580   chains in Southern Europe. Journal of cleaner production, 76, 42-54.

581   Hagberg, M. B., Pettersson, K., Ahlgren, E. O. (2016). Bioenergy futures in Sweden–

582   Modeling integration scenarios for biofuel production. Energy, 109, 1026-1039.

583   INFC - Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. (2015).

584   Estensione   e   composizione   dei   boschi.

585   https://www.sian.it/inventarioforestale/jsp/01tabelle_superficie.jsp (accessed 03 May 2018)

586   IPCC, 2007. IPCC Climate Change 2007: The Physical Science Basis. Cambridge University

587   Press, Cambridge.

588   Janssens-Maenhout, G., Dentener, F., Van Aardenne, J., Monni, S., Pagliari, V.,Orlandini, L.,

589   Klimont, Z., Kurokawa, J., Akimoto, H., Ohara, T., Wankmueller, R.,Battye, B., Grano, D., Zuber, A.,

590   Keating, T., 2012. EDGAR-HTAP: A HarmonizedGridded Air Pollution Emission Dataset Based on

591   National Inventories. European Commission Publications Office, Ispra, Italy, JRC68434, EUR

592   reportNo EUR 25 299-2012, ISBN 978-92-79-23122-0, ISSN 1831-9424.

593   Keoleian, G.A., Volk, T.A., 2005. Renewable Energy from Willow Biomass Crops: Life

594   Cycle Energy, Environmental and Economic Performance. Critical Reviews in Plant Sciences 24, 385-

595   406.

596   Lijó, L., González-García, S., Bacenetti, J., Moreira, M. T. (2017). The environmental effect

597   of substituting energy crops for food waste as feedstock for biogas production. Energy, 137, 1130-

598   1143.

599   Lijó, L., Lorenzo-Toja, Y., González-García, S., Bacenetti, J., Negri, M., Moreira, M.T., 2017.

600   Eco-efficiency assessment of farm-scaled biogas plants. Bioresource Technology, 237, 146-155.

601   Lourinho, G., Brito, P. (2015). Assessment of biomass energy potential in a region of Portugal

602   (Alto Alentejo). Energy, 81, 189-201.

603   Lovarelli D., Fusi A., Pretolani R., Bacenetti J. 2018. Delving the environmental impact of

604   roundwood production from poplar plantations. Science of the Total Environment, 645: 646.654.

605   Matsumura, Y., Minowa, T., Yamamoto, H. (2005). Amount, availability, and potential use of

606   rice straw (agricultural residue) biomass as an energy resource in Japan. Biomass and Bioenergy,

607   29(5), 347-354.

608   MISE - Ministero dello Sviluppo Economico (2012). Decreto ministeriale 6 luglio 2012 ed

609   allegati - Incentivi per energia da fonti rinnovabili elettriche non fotovoltaiche.

610   (http://www.sviluppoeconomico.gov.it/images/stories/normativa/DM_6_luglio_2012_sf.pdf)

611   Monteiro, E., Mantha, V., Rouboa, A. (2012). Portuguese pellets market: Analysis of the

612   production and utilization constrains. Energy Policy, 42, 129-135.

613   Muench, S., Guenther, E. (2013). A systematic review of bioenergy life cycle

614   assessments. Applied Energy, 112, 257-273.

615   Muth Jr, D. J., Bryden, K. M., Nelson, R. G. (2013). Sustainable agricultural residue removal

616   for bioenergy: A spatially comprehensive US national assessment. Applied Energy, 102, 403-417.

617   Nussbaumer T, Oser M. Evaluation of biomass combustion based energy systems by

618   cumulative energy demand and energy yield coefficient, International Energy Agency IEA bioenergy

619   Task 32 and Swiss Federal Office of energy. Version 1.0. Zurich: Verenum press; 2004.

620   Okello, C., Pindozzi, S., Faugno, S., Boccia, L. (2013). Bioenergy potential of agricultural and

621   forest residues in Uganda. Biomass and Bioenergy, 56, 515-525.

622   Oreggioni, G. D., Singh, B., Cherubini, F., Guest, G., Lausselet, C., Luberti, M., Strømman,

623   A. H. (2017). Environmental assessment of biomass gasification combined heat and power plants with

624   absorptive and adsorptive carbon capture units in Norway. International Journal of Greenhouse Gas

625   Control, 57, 162-172.

626   Patel, M., Zhang, X., Kumar, A. (2016). Techno-economic and life cycle assessment on

627   lignocellulosic biomass thermochemical conversion technologies: A review. Renewable and

628   Sustainable Energy Reviews, 53, 1486-1499.

629   PRé Consultants 2016. SimaPro Database Manual – Methods library. The Netherlands

630   Proto, A. R., Bacenetti, J., Macrì, G., Zimbalatti, G. (2017). Roundwood and bioenergy

631   production from forestry: Environmental impact assessment considering different logging systems.

632   Journal of Cleaner Production, 165, 1485-1498.

633   Sandin, G., Røyne, F., Berlin, J., Peters, G. M., Svanström, M. (2015). Allocation in LCAs of

634   biorefinery products: implications for results and decision-making. Journal of Cleaner Production, 93,

635   213-221.

636   Sandin, G., Røyne, F., Berlin, J., Peters, G. M., Svanström, M. (2015). Allocation in LCAs of

637   biorefinery products: implications for results and decision-making. Journal of Cleaner Production, 93,

638   213-221.

639   Scarlat, N., Dallemand, J. F., Motola, V., Monforti-Ferrario, F. (2013). Bioenergy production

640   and use in Italy: Recent developments, perspectives and potential. Renewable energy, 57, 448-461.

641   SFC-   WGII,   2008.

642   https://ec.europa.eu/agriculture/sites/agriculture/files/fore/publi/sfc_wgii_final_report_072008_en.pdf

643   (accessed 23 April, 2018)

644   Sikkema, R., Steiner, M., Junginger, M., Hiegl, W., Hansen, M. T., Faaij, A. (2011). The

645   European wood pellet markets: current status and prospects for 2020. Biofuels, Bioproducts and

646   Biorefining, 5(3), 250-278.

647   Terna, 2016. http://download.terna.it/terna/0000/0994/85.PDF (accessed 03 May 2018)

648   Tsupari, E., Arponen, T., Hankalin, V., Kärki, J., Kouri, S. (2017). Feasibility comparison of

649   bioenergy and CO2 capture and storage in a large combined heat, power and cooling system. Energy,

650   139, 1040-1051.

651   Verani, S., Sperandio, G., Civitarese, V., Spinelli, R. (2017). La meccanizzazione nella

652   raccolta di impianti di arboricoltura da legno: produttività di lavoro e costi. Forest@-Journal of

653   Silviculture and Forest Ecology, 14(1), 237.

654   Viana, H., Cohen, W. B., Lopes, D., Aranha, J. (2010). Assessment of forest biomass for use

655   as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in

656   Portugal. Applied Energy, 87(8), 2551-2560.

657   Weidema, B.P., Bauer. C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C.O.,

658   Wernet, G., 2013. Overview and methodology. Data quality guideline for the ecoinvent database

659   version 3. Ecoinvent Report 1(v3). St. Gallen: The Ecoinvent Centre.