GREENHOUSE GAS EMISSIONS OF AN AGRO-BIOGAS ENERGY SYSTEM: ESTIMATION UNDER THE RENEWABLE ENERGY DIRECTIVE

Roberto Rana^{}, Carlo Ingrao, Mariarosaria Lombardi, Caterina Tricase*

University of Foggia, Department of Economics

Via R. Caggese, 1 – 71121 Foggia (Italy)

*Corresponding author: roberto.rana@unifg.it

Abstract

Agro-biogas from energy crops and by-products is a renewable energy carrier that can potentially contribute to climate change mitigation. In this context, application of the methodology defined by the Renewable Energy Directive 2009/28/EC (RED) was performed in order to estimate the 100-year Global Warming Potential (GWP₁₀₀) associated with an agro-biogas supply chain (SC) in Southern Italy. Doing so enabled calculation of Greenhouse Gas (GHG) emission saving in order to verify if it is at least equal to 35% compared to the fossil fuel reference system, as specified by the RED. For the assessment, an attributional Life Cycle Assessment (LCA) approach according to the ISO 14040-44 (2006) was integrated with the RED methodology applied following the guidelines reported in COM(2010)11 and updated by SWD(2014)259 and Report EUR 27215 EN (2015). Moreover, primary data were collected with secondary data extrapolated from the Ecoinvent database system. Results showed that the GWP₁₀₀ associated with electricity production through the biogas plant investigated was equal to 121.79 gCO_{2eq}MJ_e⁻¹ and so a 34.52% GHG-emission saving was recorded compared to the RED reference. The highest contribution comes from biomass production and, in particular, from crop cultivation due to production of ammonium nitrate in the overall amount used for crop cultivation. Based upon the findings of the study, GHG reduction was very close to satisfying the RED target and so improvements are needed for this purpose. In particular, the authors documented that through replacement of ammonium nitrate with urea the GHG-emission saving would increase to 70.22%, thus largely satisfying the RED limit. In addition, the study highlighted that conservation practices, such as NT, can significantly enable reduction of the GHG-emissions coming from agricultural activities. Therefore, those practices should be increasingly adopted for cultivation of energy crops, because the latter significantly contribute to biogas production yield enhancement.

Keywords: *Agro-biogas, CHP, GHG-emissions, Renewable Energy Directive (RED), GWP₁₀₀*

1. Introduction

Three key political decisions marked biofuel development in the European Union (EU): the 1992 Common Agriculture Policy (CAP) reform, the 2003 biofuel directives, and the 2008 Climate and Energy Package (specifically the Renewable Energy Directive – RED). Each of those acts had important contributions in expanding the biofuel markets. In 1992, in order to regulate supply and demand for grains by reducing the area under cultivation, certain areas of land were mandatory set-aside thus allowing cultivation of no-food crops. Up to 2002, this policy led to a small development of energy crops on uncultivated hectares, though some Member States began to promote initiatives for the incorporation of biofuels with conventional fuel through tax reductions. In 2003, the CAP implemented a new award for energy crops grown beyond set-aside land and the European Commission (EC) adopted two directives aimed at promoting the use of biofuels: the Directive 2003/30/EC and the Directive 2003/96/EC (European Commission 2003a; European Commission, 2003b). The former promoted the use of biofuels or other renewable fuels for transport, establishing for 2010 the non-mandatory target of 5.75% (based on energy content) for the market share of biofuels. The latter was issued to grant tax reductions or exemptions for producers of biofuels, thereby contributing to the better functioning of the internal market (Tricase and Lombardi, 2008; Bureau et al., 2010). The last important steps were the publication of the Directives n. 28 and n. 30 (dated 23rd April 2009). The first (defined as RED) states that 10% of energy consumption in the transport sector must be produced from renewable sources by 2020. The second, namely the Fuel Quality Directive (FQD), requires a 6 % reduction of the greenhouse gas (GHG) emissions derived from combustion of the transportation fuels used in road vehicles by 2020 (European Commission 2009a; European Commission, 2009b). The sustainability of transportation biofuels raised public concerns in early 2008 when the food crisis broke out and drove international attention on the potential risks from competition for fertile land between energy crops and food crops, especially those associated with the possible impacts on consumers' welfare following increases in agricultural prices (FAO, 2013; Jose and Bhaskar, 2015). At the same time, the concern of the energy and GHG balance of EU biofuels represented another critical controversy (Tricase and Lombardi, 2012). Issues were mostly related to indirect land use change

(ILUC), that is the indirect market-mediated effects of first generation biofuels (i.e., those produced from food crops like corn bioethanol) that can result in emissions of GHGs outside system boundaries. The potential risks and attribution of ILUC effects to biofuels are still largely debated today by the environmental impact assessment community (Kløverpris and Mueller, 2013; Finkbeiner, 2014; Schmidt et al., 2015). The European Commission has explored possible options to mitigate worries from ILUC by elaborating the Staff Working Document - SWD(2012) (European Commission, 2012). In particular, this latter is a draft proposal, issued on the 17th October 2012, that defines a precautionary threshold (initially 5%, then adjusted to 7% in 2015) for the share of first generation biofuels in the transportation market (European Commission, 2012; European Parliament, 2015). Its main purpose is to enhance the production of second-generation biofuels, e.g. from waste feedstock and residues, which can usually ensure larger GHG savings (EBTP, 2015). This new policy framework will surely affect the rate at which biofuels can penetrate the EU transport sector, which is, in 2014, based on an average target of 4.9%, a value that has been increasing since 2005 (when it was set equal to 1.03%) (EurObserv'er, 2015).

Until this proposal will not be converted into law, the current methodology, officially adopted by the European Commission to assess the environmental sustainability of transportation biofuels, is the RED for liquid fuels. The COM(2010)11, updated according to SWD(2014)259 and the JRC Report EUR 27215 EN of 2015, is on the contrary applied for solid and gaseous biofuels (European Commission, 2010; European Commission, 2014; Giuntoli et al., 2015). Article 17 of the directive defines five criteria that biofuel and bioliquid production systems should consider: i) reduction of greenhouse gas emissions by at least 35% (up to 50% in 2017) in comparison with fossil fuels; ii) protection of biodiversity; iii) protection of land with high carbon stock; iv) protection of un-drained soil; v) guarantee of good agricultural and environmental conditions (Lombardi et al., 2014). Economic operators can benefit from market incentives for biofuel production only under conditions of evident compliance with those criteria.

The RED and followings provide guidelines to assess the climate change impacts of biofuel production systems by accounting for all GHG-emissions released from the entire value chain, from the resource supply to the final energy products. These

guidelines are based on the Life Cycle Assessment (LCA) approach, which is frequently implemented at scientific and corporate levels to understand the environmental impacts of products and services (Cherubini and Strømman, 2011; Singh et al., 2013). The important methodological progress, indicated by SWD(2014)259, and better elaborated and specified by the JRC Report EUR 27215 EN, concerns the LCA approach for biogas systems producing both electricity and heat, and biomethane. Specifically, the updates are related to some crucial points such as: mass balance rule; Fossil Fuel Comparator (FFC); new GWP₁₀₀ values (Giuntoli et al., 2015; Agostini et al., 2015; Styles et al. 2015). As regards the first aspect, article 18 of the RED states that a mass balance system is recommended to economic operators to verify the sustainability of their biofuel supply chain and to satisfy the aforementioned criteria for each type of raw materials used. However, when it comes to co-digestion process and so the feedstock is made of multiple locally-produced raw materials, this approach could cause underestimation of the GHG-emission saving values. The SWD(2014)259 suspended this system for biogas SC and presented a formula to calculate GHG-emissions of co-digestion systems by combining the defaults values for single-feedstock digestion. Also for FFCs, the new guidelines updated the values according to the average GHG intensity of fossil fuels brought on the EU transportation and energy market. Specifically, that one related to electricity changed, passing from 198 to 186 gCO₂eqMJ_e⁻¹, assuming a marginal mix of present and perspective fossil power production technologies and feedstock. Finally, as already resulting from Giuntoli et al., (2015) and Edwards et al. (2014), the conversion factors into CO₂eq to be considered for biofuel SC environmental assessments have been updated according to the guidelines issued by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007): 25 for methane (CH₄) and 298 for nitrous oxide (N₂O). From the literature review, the authors have noticed that only few scientific papers estimated the GHG-emissions associated with an agro-biogas under the RED and all of them focussed specifically upon biomethane for usage as transport fuel (Buratti et al., 2013; Manninen et al., 2013; Tufvesson et al., 2013; Uusitalo et al., 2014). As regards the field of biogas utilisation for electricity production numbers of LCAs have been

recently developed, mainly focussing upon specific EU geographic areas under co-digestion conditions (Lansche et al., 2012; Meyer-Aurich et al., 2012; Bachmaier et al. 2013; Bacenetti et al., 2013). Other studies, such as Boulamanti et al. (2013), Agostini et al. (2015) and Styles et al. (2015) have dealt with environmental sustainability assessment in biogas systems, mainly through application of LCA, and have obtained important methodological progress as compared to the RED methodology. Therefore, the authors believe that further case-studies are needed to enrich the specialised literature currently related to biogas SCs, thus supporting the international debate on the RED application by providing additional inventory data and results.

In this context, this work was aimed at estimation of the GWP_{100} associated with an agro-biogas SC sited in Southern Italy that includes a co-digestion plant. The authors used the results from the study to verify compliance with the methodology proposed by the RED and subsequent updates as regards electricity production.

Finally, it should be observed that the study falls within a research designed to assess the GHG-emissions associated with the aforementioned SC. To do so, an in-depth preliminary analysis of the inventory flows (materials and energies) was performed in order to create the building block for the present work and the one carried out by Ingrao et al. (2015) dealing with Carbon Footprint application.

2. Materials and methods

This section was dedicated to description of the agro-biogas plant investigated and to discussion of the methodological approach used for the assessment.

2.1 Description of the analysed system

The plant under study is located in the province of Foggia (Apulia, Italy) and is based upon an integrated system producing biogas from a variety of feedstocks, such as energy crops (maize and triticale), Durum Wheat (DW) by-products from grain mills (named “tritello”) and animal effluents (manure and sewage). The system is mainly constituted by: two anaerobic digesters operating under thermophile conditions; one desulphurisation plant; and, a Combined Heat and Power (CHP) plant. The conversion electrical efficiency was calculated following the Annex 1 (1.b) of the COM(2010)11

from the daily amounts of Purified Biogas (PB) input (12,000 m³) and produced electricity (24,000 kWh_e): the obtained values is equal to 36.47%.

The integrated system is broken down in three major stages (or subsystems):

- SS1 - biomass production (Figure 1);
- SS2 - biomass transport (Figure 2);
- SS3 - biogas production plant (Figure 3).

Each figure shows the major process stages, and material and energy input requirements. Hereby some characteristics of the biomass production chain were presented. For instance, tritello is a DW grain milling by-product that is produced in the amount of 0.045 kg of processed grains and is derived from a fine bran sifting consisting of small bran flakes, germ fragments and small amounts of flour (Ingrao et al., 2015). The use of tritello as a feedstock component is a promising option because it plays a significant role in the Apulia region's agro-economy (AgriIstat, 2014).

Additionally, for the study development it was considered that 10% of the crops produced is made of harvesting and chopping residues that are left on the ground with soil cover function. These residues create a mulch into which direct seeding can take place, according to the No-Tillage (NT) standard practice (Derpsch et al., 2014). Farmers thus enable both preservation and enhancement of soil quality and productivity, thanks to Soil Organic Carbon (SOC) accumulation. The use of NT practices is particularly recommended in areas at risk of desertification, like the one in question, because it contributes to reduction of groundwater depletion and salinization, preventing the negative effects of intensive-use and erosion of agricultural lands. Both maize and triticale are chopped and then transported to the agro-biogas plant where they are ensilaged.

The production (cattle breeding) and management of the animal effluents (sewage and manure) were excluded from the system boundaries because a zero-burden approach was applied and so only the GHG-emissions for their transportation to the anaerobic digestion plant were taken into account. The digestate Solid Fraction (SF) and Liquid Fraction (LF) are partially reused as organic fertilisers for biomass production in the daily amounts indicated in Fig. 3. In order to increase soil organic matter content, the farm integrates mineral (50%) with organic (50%) fertilisation for maize and triticale using the digestate solid and liquid fractions recovered from the biogas plant. In this

way, the farm contributes to reduction of organic matter loss and environmental impact due to chemical fertiliser production and spreading.

On the other hand, DW land organic-farming is not possible because the amounts of digestate SF and LF remaining from maize and triticale land cultivation cover less than 5% of the related nutrient (N, P, K) requirements (Ingrao et al., 2015). This is mainly due to the huge amount of DW that is needed to produce the tritello required for biogas production: therefore, a 100% mineral fertilisation is practiced in this case. In particular, about 80% of the digestate LF obtained is reused within the anaerobic digestion plant as feedstock, whilst the remaining 20% is reused for land fertigation. Finally, the amount of electricity and heat internally used by the plant is 8% and 48% of the total production, respectively. Electricity is used to run the plant and the heat is recovered to warm both the substrate within the digestion chamber and the water for agro-biogas purification.

Fig. 1. Process flow diagram and material and energy inputs of feedstock biomass production system
(values are per ha of cultivated soil)

Fig. 2. Process flow diagram and material and energy inputs of the biomass transport system

Fig. 3. Agro-biogas plant: biogas production and transformation into energy (daily values)

The main technical data and information related to the plant investigated are summarised in Fig. 4. Further information are available in Ingrao et al. (2015) where a more detailed description of the plant is available.

Fig. 4. Agro-biogas plant's datasheet

2.2 Study development criteria

This study was aimed at estimation of the GHG-emissions associated with an agro-biogas located in Southern Italy through application of the RED methodology. This was done following the guidelines reported in COM(2010)11 and the subsequent changes introduced by the SWD(2014)259. In this way, it was possible for the authors to verify

satisfaction of the GHG-emission saving imposed by the RED for what concerns to electricity production. Moreover, for the assessment the LCA approach was followed according to the ISO 14040-44 (ISO, 2006a; ISO 2006b), so representing the base structure for the study. The latter is part of a research designed for estimation of the GHG-emissions associated with the SC in question. For this purpose, an in-depth preliminary analysis of the inventory flows (materials and energies) was performed in order to create the building block for the subsequent assessments. In this regard, it should be observed that primary data were provided by the farm and then combined with background data taken from Ecoinvent (2011). Such a database system was accessed because, according to Siracusa et al. (2014), it is acknowledged as a reliable background data source. Moreover, as stated by Frishknecht and Rebitzer (2005), it accommodates most of the background materials and processes often required for development of LCA-related studies. As regards the GHG-emission assessments provided by the research, they were performed using two different methodologies: the Carbon Footprint according to the ISO 14067:2013 (ISO, 2013) in Ingrao et al. (2015); and, the RED in this paper. The whole research was developed, because agro-biogas SCs are acknowledged worldwide as not being free from GHG-emissions. Such an aspect emphasises upon the need for environmental performance evaluations and improvements. Additionally, with specific regard to the RED the literature review showed deficiencies in the application of this methodology as regards electricity production from agro-biogas. Therefore, the authors believe that this paper could enrich the specialised literature currently available in the field.

According to the LCA approach, both functional unit and system boundary were defined. In this case, the former was identified with 1 MJ_{PB} in order to be consistent to the RED requirements and so it was used as a reference for GHG-emission calculation. As regards the system boundaries, the latter included three subsystems interrelated through material and energy flows. Furthermore, they were expanded in order to comprise management of the digestate reused within the whole system.

Biogas distribution was not taken into consideration because, once purified, biogas is utilised on site for production of both electricity and heat.

Finally, it is worth to underline that the present study assesses only the GHG-emission saving for electricity production, in the light of the specific characteristics of the biogas plant investigated.

2.2.1 Methodological approach

Calculation of the GHG-emissions associated with biomass production, input material transportation and, both biogas and energy production was performed following the equation contained in the annex I of the COM(2010)11, as reported below:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \quad (1)$$

where E is the total emissions from the production of the fuel before energy conversion resulting from the following contributions: raw material cultivation (e_{ec}); carbon stock change caused by land use change normalised to 1 year (e_l); processing (e_p); transport and distribution (e_{td}); fuel use (e_u); soil carbon accumulation via improved agricultural management (e_{sca}); carbon capture and geological storage (e_{ccs}); carbon capture and replacement (e_{ccr}).

Those contributions were expressed as $\text{gCO}_{2\text{eq}}\text{MJ}_{\text{PB}}^{-1}$ and were calculated accounting for the GHGs recommended by the RED (carbon dioxide, methane and nitrous oxide) and measured considering the conversion factors suggested by SWD(2014)259, and Giuntoli et al. (2015): 1, 25 and 298 $\text{gCO}_{2\text{eq}}\text{g}_{\text{GHG}}^{-1}$, respectively. Moreover, e_{ccs} and e_{ccr} were considered as equal to zero because, in the particular case, there is no carbon capture due to geological storage and to carbon replacement. Same assumption was done for e_l because no land use changes were considered. In particular, there is no direct land use change, since the surface invested for feedstock-crop cultivation was already a cropland. However, due to several deficiencies and uncertainties associated with the modelling of ILUC, there is no consensus yet on how those effects should be considered by the RED methodology. This is because, as already clarified in the introduction, the SWD(2012) has not yet undergone legal-linguistic finalisation: therefore in this paper the ILUC scenario was not calculated.

In addition, as per e_u , according to the COM(2010)11 (Annex I), this was assumed to be zero because, similarly to Ingrao et al. (2015), an implicit sequestration approach was used for GWP_{100} calculation, and so the CO_2 flow within biofuels was neglected. This resulted from assuming CO_2 -in as being equal to CO_2 -out and so, the related net-flow is

zero (Johnson, 2009). Additionally, the biomass feedstocks considered in this studies are indeed mostly annual crops or species with very short turnover times. CO₂ emissions from biogas combustion can thus be considered climate neutral because of the very short time scale of the carbon cycle/climate system perturbation (Cherubini et al., 2014). All the other factors were calculated as discussed in the next section considering GHG-emissions associated with the three subsystems defined; in particular: calculation of e_{ec} and e_{sca} relates to subsystem 1 (biomass production); e_p is referred to subsystem 2 (agro-biogas plant); e_{td} was done as regards subsystem 3 (transport system).

Since it comes to co-digestion, the following equation was derived from equation 1 based upon the SC investigated.

$$E_{SC(n)} = e_{ec} + e_p + e_{td} - e_{sca} \quad (2)$$

Moreover, for consistency with the requirements of the recent SWD(2014)259, equation 2 was applied to the each feedstock pathway considered (n), assuming that it constitutes the whole substrate.

Subsequently, $E_{SC(n)}$ was used for calculation of the GHG-emissions associated with the co-digestion process following the procedure detailed within SWD(2014)259. Doing so enabled weighting the contribution to GHG-emission from each feedstock mixture component based upon series of factors, such as biogas yield (Y), volatile solids (VS) and moisture contents, biogas low heating value (LHV) and annual input of the feedstock to the digester.

The calculation procedure considered included the following equations:

$$E_{SC} = \sum_1^n (S_n \times E_{SC(n)}) \quad (3)$$

where:

- E_{SC} = total GHG-emissions from the analysed SC expressed as $gCO_{2eq}MJ^{-1}_{PB}$;
- S_n = share of feedstock-n in energy content;
- $E_{SC(n)}$ = emission in $gCO_{2eq} MJ^{-1}_{el}$ from feedstock-n.

In turn, S_n was calculated from the energy yield per kilogram of wet input feedstock-n (P_n), expressed as $MJkg^{-1}$ and the weighting factor per feedstock-n (W_n), following equation (4):

$$S_n = (P_{n(PB)} \times W_n) / \sum_1^n (P_{n(PB)} \times W_n) \quad (4)$$

where:

$$P_{n(PB)} = Y_{n(PB)} \times VS_n \times LHV_{PB(n)} \quad (4a)$$

$$W_n = (I_n / \sum_1^n I_n) \times [(1 - AM_n) / (1 - SM_n)] \quad (4b)$$

where:

- $Y_{n(PB)}$ is the energy production yield per feedstock-n and was calculated considering that 1 m³_{PB} is obtained from 0.92 m³ of biogas released from the digestion plant;
- I_n = annual input to digester of feedstock-n (tonnes of fresh matter);
- AM_n = average annual moisture of feedstock-n (kg water/kg fresh matter);
- SM_n = standard moisture for feedstock-n.

Then, based upon the COM(2010)11 E_{SC} allocated to PB (E_{SC_PB}) was calculated. For this purpose, an energy-content based allocation was performed according to the RED, considering the digestate fractions that are not reused within the system analysed. In fact, as shown in Fig. 3, those fractions fall outside of the system border and so were considered as co-products. Then, according to COM(2010)11 (Annex I – point 1.b), E_{SC_PB} was divided by the electrical efficiency in order to obtain the total GHG-emissions associated with electricity production (EC_{el}).

In this way, the authors could calculate GHG-saving in order to verify that the latter is at least equal to the RED limit of 35%. Calculation was performed according to the equations contained in the annex I (point 3) of COM(2010)11 and reported below for completeness reasons:

$$GHG_{saving_{el}} = (E_{F(el)} - EC_{el}) / E_{F(el)} \quad (5)$$

where E_{F(el)} are the emissions from the fossil fuel comparator for electricity (198 gCO_{2eq}MJ_e⁻¹) (European Commission, 2010).

2.2.1.1 GHG-emission calculation

The assessment was carried out calculating each feedstock contribution to GWP₁₀₀, according to equation (2), and then E_{SC} based upon equation (3). For this purpose, it was needed first to calculate a set of Emission Factors (EFs) accessing the Ecoinvent database production models; the EFs considered are those associated with:

1) the diesel utilised for the agricultural activities required for each crop production ($D_{agr.act}$) and for transportation of the materials demanded for each crop farming (seeds, fertilisers and so) and anaerobic digestion (feedstock) (D_{M_dT});

2) the electricity and the natural gas utilised for DW grain milling and other internal farm-equipment.

EF calculation was performed by extrapolating from Ecoinvent, for each of those items, the emissions of CO_2 , N_2O and CH_4 based upon the related production models contained in the aforementioned database. Then, the aforementioned GWP_{100} conversion factors and the diesel LHV (reported within the RED) were taken into account, in order to express those EFs as $gCO_{2eq}MJ^{-1}_{PB}$. Doing so enabled comparability to the related values currently available in the scientific literature so to have a better understanding of the goodness of the method elaborated.

Furthermore, $P_{n(PB)}$ calculation was required for each feedstock according to equation (4a), and the obtained values were shown in Table 1, together with the other multiplication factors, namely $Y_{n(PB)}$, VS_n and $LHV_{PB(n)}$. In particular, $LHV_{PB(n)}$ was calculated for each feedstock crop as $35.9 MJ(m^3)^{-1} \cdot CH_4(\% vol.)$, according to SWD(2014)259 and Giuntoli et al. (2015).

Table 1
 P_n calculation results

Finally, it should be observed that a correction factor (c_f) of 0.85 was applied in order to avoid accounting for the emissions from manufacture of the machineries (transport means included) and the equipment utilised for materials, fuels and energy production. Such a factor was calculated considering that, by performing internal checks upon the Ecoinvent models related to those materials and energy production, an average 15% influence on their GHG-emissions was evidenced. This correction was performed in order to make the method elaborated consistent with the requirements established by the RED methodology in the Annex I (point 1.a) of COM(2010)11.

Below, the calculation performed was described in details for each subsystem and feedstock-n analysed.

Biomass production

For $e_{ec(n)}$ estimation, equation (6) was followed:

$$e_{ec(n)} = e_{ec(C.C.)_n} + e_{ec(F.P.)_n} \quad (6)$$

where:

- $e_{ec(C.C.)_n}$ is referred to cultivation of each feedstock crop (maize, triticale and DW);

- $e_{ec(F.P.)_n}$ stands for feedstock production and was calculated taking into account

both ensilage of maize and triticale and production of tritello from DW grain

milling.

In particular $e_{ec(C.C.)_n}$ in equation (6), was calculated as the sum of the emissions

associated with: 1) $e_{M_dP(n)}$, production of the materials for crop cultivation (i.e. seeds,

ammonium nitrate, glyphosate and other herbicides, and fungicides); 2) $e_{agr.act(n)}$, diesel

consumption for agricultural activities, such as seeding, irrigation, chopping and

harvesting, fertiliser administration, pest management; and, 3) $e_{N_2O(n)} = e_D + e_{IND}$, direct

and indirect emissions of N_2O from soil according to the RED.

In particular:

1) $e_{M_dP(n)}$ was calculated following equation (7a) for maize and triticale, whilst equation

(7b) for DW. It was done so because DW is milled for production of series of by-

products, including Tritello that, in this case, is used as feedstock to co-digestion.

$$e_{M_dP(n)} = c_f \times 1/P_{n(PB)} \times \sum_1^4 [EF_{M_dP(i)} \times M_{d(i)}] \quad (7a)$$

$$e_{M_dP(tritello)} = c_f \times Y_T \times 1/P_{n(PB)} \times \sum_1^4 [EF_{M_dP(i)} \times M_{d(i)}] \quad (7b)$$

where:

- “n” is referred to maize, triticale and tritello (Table 1);

- $M_{d(i)}$ is the i th-material demand for each feedstock-crop production. It is expressed as

$kgkg_n^{-1}$ for maize and triticale, and as $kgkg_{DW}^{-1}$ for the tritello-related biogas

pathway. In particular, data were elaborated from those provided by the farm

considering each feedstock crop net-production yield, namely 22,500, 58,500 and

4,050 $kg ha^{-1}$ for triticale, maize and DW, respectively;

- $EF_{M_dP(i)}$ (expressed as $gCO_{2eq}kg(M_dP)^{-1}$) was calculated from the emissions of CO_2 ,

N_2O and CH_4 , extrapolated from Ecoinvent based upon the production model of the

i th M_d . Such a calculation was done using the GWP_{100} conversion factors anticipated

in the previous section;

- Y_T stands for the ratio between kg_{DW} and $kg_{tritello}$ and is equal to 1, based upon the mass allocation already performed by Ingrao et al. (2015) for the DW milling phase. For completeness reasons, in Table 2 the authors listed both EF_{M_dP} and M_d values.

Table 2

Values for calculation of the emissions from production of material inputs to crop farming ($e_{mat.prod}$)

2) to model crop cultivation activities, it was proceeded the way of raw material production distinguishing maize and tritcale from DW. For this purpose, equations (8a) and (8b) were implemented as shown below:

$$e_{agr.act.(n)} = c_f \times \frac{1}{P_{n(PB)}} \times LHV_{Diesel} \times \sum_1^6 [EF_{D_{agr.act(i)}} \times D_{agr.act(i)}] \quad (8a)$$

$$e_{agr.act.(tritello)} = c_f \times Y_T \times \frac{1}{P_{n(PB)}} \times LHV_{Diesel} \times \sum_1^6 [EF_{D_{agr.act(i)}} \times D_{agr.act(i)}]$$

(8b)

where:

- “n” refers to maize, tritcale and tritello;
- $D_{agr.act(i)}$ is the diesel consumption provided by the farm for the i th agricultural activity involved and measured as $kg_{(D_{agr.act})} kg_n^{-1}$ (Table 3);
- $LHV_{Diesel} = 43 \text{ MJ kg}^{-1}$, as extrapolated from Annex III of the RED;
- $EF_{D_{agr.act(i)}}$ is the emission factor for production and combustion of the diesel demanded for the operation of the agricultural means and equipment utilised related to the i th activity.

Table 3

Diesel consumption amounts inventoried for calculation of the emissions due to agricultural activities involved in crop farming ($e_{agr.act.}$)

3) $e_{N_2O(Tot)n_RED}$ calculation was done based upon Ingrao et al. (2015). In particular, the authors of that paper used 2006-IPCC guidelines (IPCC, 2006) to estimate both direct and indirect emissions of N_2O (expressed as kg_{ha}^{-1}). In the present study, those values were converted from kg_{ha}^{-1} into $gCO_{2eq} MJ_{PB}^{-1}$ in order to be consistent

with application of the RED and subsequent updates. For this purpose, the following equation was used:

$$e_{N_2O(Tot)n_RED} = [(e_{N_2O(Tot)n_IPCC} \times p_n \times 1/P_{n(PB)})/1000] \times CF_{GWP_{100}(N_2O)} \quad (9a)$$

$$e_{N_2O(Tot)DW_RED} = [(e_{N_2O(Tot)tritello_IPCC} \times p_n \times Y_T \times 1/P_{n(PB)})/1000] \times CF_{GWP_{100}(N_2O)} \quad (9b)$$

where:

- n stands for maize and tritcale;
- $e_{N_2O(n)_RED}$ stands for the direct and indirect N_2O -emissions from soil, expressed as $gCO_{2eq}MJ_{PB}^{-1}$ associated with the single feedstock-crop;
- $e_{N_2O(nt)_IPCC}$ stands for the direct and indirect N_2O -emissions from soil calculated for each feedstock-crop based upon application of the IPCC-methodology ($kg\ ha^{-1}$). The related values were shown in Table 3;
- p_n stands for the reverse of each feedstock-crop production net-yield and is equal to: $1.709E-5\ hakg_n^{-1}$ (maize), $4.444E-5\ hakg_n^{-1}$ (tritcale) and $2.469E-4\ hakg_n^{-1}$ (DW);
- $CF_{GWP_{100}(N_2O)}$ is the GWP_{100} conversion factor of N_2O according to IPCC (2007) and equal to $298\ gCO_{2eq}\ gN_2O^{-1}$.

Table 4

Values of direct and indirect N_2O -emissions form soil calculated according to 2006 IPCC guidelines¹

In order to complete $e_{ec(n)}$ estimation as requested by the RED, it was needed to calculate $e_{ec(F.P.)_n}$ for accounting for the GHG-emissions associated with both ensilage of maize and tritcale, and DW grain milling for tritello production. In the case of ensilage, calculation was done based upon the following formula:

$$e_{ec(F.P.)_ensilage(n)} = c_f \times D_{ensilage(n)} \times LHV_{diesel} \times EF_{D_{ensilage(n)}} \times 1/P_{n(PB)} \quad (10)$$

where:

- $D_{ensilage(n)}$ is the daily average consumption of diesel for ensilage and is equal to $2.65E-4\ kgkg_{maize}^{-1}$ and to $2.74E-4\ kgkg_{tritcale}^{-1}$ according to the information

¹ Extrapolated from Ingrao et al. (2015)

supplied by the farm $EF_{D_{ensilage}}$ is the emission factor associated with production and combustion of the diesel demanded for chopped maize and triticale ensilage. From calculation, it resulted to be equal to $85.49 \text{ gCO}_{2eq}\text{MJ}^{-1}$.

GHG-emissions associated with production of tritello was calculated from consumption of electricity and natural gas related to the DW grain milling phase, according to the following approach:

$$e_{ec(F.P.)_tritello} = e_{ec(F.P.)_electricity} + e_{ec(F.P.)_nat.gas} \quad (11)$$

where:

$$e_{ec(F.P.)_electricity} = c_f \times C_E \times Y_T \times 1/P_{n(PB)} \times EF_{el} \quad (11a)$$

$$e_{ec(F.P.)_nat.gas} = c_f \times C_{NG} \times Y_T \times 1/P_{n(PB)} \times EF_{nat.gas} \quad (11b)$$

and:

- in this case, “n” is referred only to tritello;
- C_E and C_{NG} represent the consumption volumes of both electricity ($0.08 \text{ kWh}_{el}\text{kg}_{DW(PB)}^{-1}$) and heat (from natural gas) ($0.36 \text{ MJ}_{NG} \text{ kg}_{DW(PB)}^{-1}$) in the milling phase per kg of DW;
- EF_{el} and $EF_{nat.gas}$ are the emission factors for electricity and natural gas extrapolated from SWD(2014)259 and equal to $669.6 \text{ gCO}_{2eq}\text{kWh}_{el}^{-1}$ and $72 \text{ gCO}_{2eq}\text{MJ}_{NG}^{-1}$, respectively. In particular, the former was calculated considering the Fossil Fuel Comparator (FFC) proposed by SWD(2014)259 and equal to $186 \text{ gCO}_{2eq}\text{MJ}_{el}^{-1}$. The authors did so since, as clarified by Agostini et al. (2015), a difference in emissions between consumption and FFC would create fictitious emissions savings. In particular, the FFC is referred to the power supplied from the electricity grid and assumes a marginal mix of present and perspective fossil power production technologies and feedstocks. The power mix considered is the following: 50% natural gas fired CCGT-plants (with gas sourced from a mixture of sources, from short/long distance as well as LNG), 25% coal fired IGCC plants, and 25% conventional coal [SWD(2014)259].

Finally, e_{sca} was calculated because NT enables SOC and so contributes to enhanced physical, chemical and biological quality of the soil and to reduced GHG-emission in agricultural management systems. Therefore, calculation was performed using the annual amount of carbon accumulated in the soil, as already reported within Ingrao's et al. (2015) paper and equal to 0.35 tha^{-1} meaning $1.295\text{E}6 \text{ gCO}_2\text{ha}^{-1}$ (A_{CO_2}); as

previously done, the following equations were elaborated for maize and triticale, and DW and applied subsequently:

$$e_{sca(n)} = A_{CO_2} \times p_n \times 1/P_{n(PB)} \times CF_{GWP_{100}(CO_2)} \quad (13a)$$

$$e_{sca(DW)} = A_{CO_2} \times p_n \times Y_T \times 1/P_{n(PB)} \times CF_{GWP_{100}(CO_2)} \quad (13b)$$

where $CF_{GWP_{100}(CO_2)}$ is the GWP_{100} conversion factor of CO_2 according to IPCC (2007) and equal to $1 \text{ gCO}_{2eq} \text{ gCO}_2^{-1}$.

Material transportation

Calculation of the GHG-emissions associated with the transport system (e_{td}) was done considering the following two stages: 1) transport of the materials required for crop cultivation, such as seeds, fertilisers, pesticides and both solid and liquid fractions of digestate for organic fertilisation; 2) transport of feedstock biomasses from the production sites to the anaerobic digestion plant in order to be processed into biogas. As per the first case (point 1), equations 8(ab) were applied but the diesel type and amount as well as the EF associated with its production and consumption ($EF_{D_{MdT}}$) were updated to the transport scenario analysed: in fact, a low-sulphur diesel is utilised for the case. Therefore, equations 14(ab) were specifically elaborated and reported below:

$$e_{mat.transp.(n)} = c_f \times 1/P_{n(PB)} \times LHV_{Diesel} \times EF_{D_{MdT}} \times \sum_1^6 D_{MdT(i)} \quad (14a)$$

$$e_{mat.transp.(tritello)} = c_f \times Y_T \times 1/P_{n(PB)} \times LHV_{Diesel} \times EF_{D_{MdT}} \times \sum_1^6 D_{MdT(i)} \quad (14b)$$

where, for maize, triticale and DW, $D_{MdT(i)}$ is the diesel consumption provided by the farm for transportation of the i th input-material (seeds, ammonium nitrate, etc.), measured as $\text{kg}_{(MdT)} \text{ kg}_n^{-1}$.

Moreover, diesel consumption amounts were extrapolated from Ecoinvent considering the distance travelled, the amount of transported material and the characteristics of the means utilised (lorry range and European emission standards). So, based upon the latter information, it was possible for the authors to identify the most suitable model in Ecoinvent to be considered for calculation: in particular, it refers to the operation of an average European Euro5 3.5-16t lorry. Then, the emission factor associated with diesel

production and consumption was estimated and equalled 89.6 gCO_{2eq}MJ⁻¹. For completeness reasons, diesel consumption (D_{MdT}) values were shown in Table 5.

Table 5

Diesel consumption amounts for transportation of material demanded for crop farming

Transport of DW grains to the milling plant for production of tritello was also taken into account for the assessment. Its modelling was performed by implementing equation (14c) from equation (14b):

$$e_{DW_transp} = c_f \times Y_T \times \frac{1}{P_{n(PB)}} \times LHV_{Diesel} \times EF_{D_{MdT}} \times D_{MdT} \quad (14c)$$

In particular, the diesel consumption (for DW transportation), represented by D_{MdT} in the equation, was quantified in 7.52E-4 kgkg_{DW}⁻¹ and the transport distance (17 km) from the cultivated land to the milling plant.

Same updating operation was done in equation (14a) in order to model transportation (to the anaerobic digestion plant) of all the feedstock components, namely maize, tritcale, tritello and animal effluents. For this purpose, equation (14d) was applied and the D_{MdT} values shown in Table 6 were accounted for.

$$e_{feedstock-n(transp)} = c_f \times \frac{1}{LHV_{PB(n)}} \times LHV_{Diesel} \times EF_{D_{MdT}} \times D_{MdT(n)} \quad (14d)$$

Table 6

Diesel consumption amounts for transportation of feedstock components to the agro-biogas plant

Agro-biogas plant

The emissions associated with this subsystem were identified as e_p, namely the emissions from the whole agro-biogas plant that includes anaerobic digestion and purification treatment. In this regard, it should be observed that:

- the amounts of electricity and heat required by the whole process during the plant working time are supplied by the CHP engine and represent the 8 and 48% of the totals produced, respectively. Therefore, the related emissions were not taken into

account because already included in the production of 1 kWh_e and 0.987 kWh_h (Ingrao et al., 2015);

- desulphurisation was not accounted for because the amounts of auxiliary resources and materials utilised are very low and so the authors considered the related contributions to the GWP₁₀₀ as possible to be neglected.

However, during the plant maintenance period (30 days up to 365 per year) when the CHP is out of service, electricity and heat consumption for the mixers and the other internal devices was taken into account for the assessment. This was done considering that, based upon information provided by the farm, electricity is supplied by the national grid and heat is burned in a condensing modulating boiler system with nominal power of almost 240 kW. Therefore, equations (15a) and (15b) were implemented for calculation of the related GHG-emissions considering consumption of 1920 kWh_ed⁻¹ for electricity and 11.370,24 kWh_hd⁻¹ for heat, as provided by the farm.

$$e_{p(n)el_sel.co} = C_{el_sel.co} \times 1/LHV_{PB} \times EF_{el} \quad (15a)$$

$$e_{p(n)NG_sel.co} = C_{NG_sel.co} \times 1/LHV_{PB} \times EF_{NG} \quad (15b)$$

where:

- $e_{p(el_sel.co)}$ and $e_{p(NG_sel.co)}$ are the emissions associated with the internal consumption of electricity and heat (from natural gas) and considered as to be part of SS3;

- $C_{el_sel.co}$ and $C_{NG_sel.co}$ are the self-consumption values for electricity and heat per m_{PB}^3 , provided by the farm and equal to 0.16 kWh and 3.42 MJ, respectively.

Furthermore, uncontrolled losses of CH₄ being originated from leakage or deficient technology were considered as negligible because the plant under study is a newly constructed one.

Emission weighting

In this phase, the calculated emissions were weighted according to equations (3) and (4) using the data reported in Table 7.

Table 7

Factors used for weighting of each feedstock component contribution to GHG-emission

In particular, the values of AM_n were provided by the farm after development of appropriate laboratory test, whilst those of SM_n were extrapolated from specialised papers and/o reports, as follows: maize and animal effluents (Giuntoli, et al., 2015); Tritello (AGER, 2002); Triticale (Castelli, 2011).

2.2.1.2 Co-products allocation

In order to account for the amounts of digestate fractions (SF and LF) that are not reused within the system and so are modelled as co-products, allocation by energy content was done. For this purpose, laboratory tests were performed upon samples of biogas and of the exceeding digestate fractions so as to obtain the related LHVs, as listed below:

- SF: 0.563 MJkg^{-1} ;
- LF: 0.457 MJkg^{-1} ;
- Agro-biogas (from all the feedstock mixture): $19.74 \text{ MJ(m}^3)^{-1}$.

Then, the energy amount (EAs) per m^3 of PB was evaluated considering the amounts of product and co-products, as shown in equations 16 and 17.

$$EA_{(Co-Prod)_{PB}} = LHV_{(Co-Prod)} \times A_{(Co-Prod)_{PB}} \quad (16)$$

$$EA_{PB} = LHV_{(PB)} \times D_{PB} \quad (17)$$

where:

- $LHV_{(Co-Prod)}$, expressed as MJkg^{-1} , is referred to the aforementioned SF and LF from digestate centrifugation;
- $A_{(Co-Prod)_{PB}}$ is the amount of each aforementioned fraction per m^3 of PB, expressed as $\text{kg(m}^3_{PB})^{-1}$;
- D_{PB} is the PB density which was obtained by performing laboratory tests and resulted in $1.09 \text{ kg(m}^3_{PB})^{-1}$.

So, the allocation percentages (P_{Alloc}) for biogas and both SF and LF were calculated according to equation (18):

$$P_{Alloc[i(i=SF,LF,pb)]} = \left\{ \frac{EA_{i(i=SF,LF,PB)}}{[EA_{(SF)_{PB}} + EA_{(LF)_{PB}} + EA_{PB}]} \right\} \times 100 \quad (18)$$

and resulted in: $P_{Alloc(SF)} = 4.18\%$; $P_{Alloc(LF)} = 0.80\%$; $P_{Alloc(PB)} = 95.02\%$.

Once E_{SC} was allocated to PB using the aforementioned percentages, it was added the emissions resulting from un-combusted methane losses that were assumed as equal to 1% of the methane contained per m^3 of PB. This was done because low percentages (0.8-10%) have been documented over the years by several studies (Dressler et al., 2012; Lijò et al., 2014; Lijò et al., 2015) and also because the whole plant, including the CHP, is recently built. Therefore, the following formula was elaborated for quantification those losses that were expressed as $gCO_{2eq}MJ^{-1}$.

$$CH_{4(uncomb.losses)}$$

$$= \%CH_{4(loss)} \times C_{CH_4(FM)} \times 1/LHV_{PB(FM)} \times \delta_{CH_4} \times CF_{GWP_{100}(CH_4)}$$

(19)

where:

- FM stands for “feedstock mixture”;
- $\%CH_4 = 1\%$;
- $C_{CH_4(n)}$ = methane content (m^3) per m^3 of biogas for each feedstock crop;
- δ_{CH_4} (methane density) = $716 g/Nm^3$;
- $CF_{GWP_{100}(CH_4)}$ is the GWP_{100} conversion factor of CH_4 according to IPCC (2007) and equal to $25 gCO_{2eq} gCH_4^{-1}$.

3. Results and discussion

The calculation procedure applied gave a result of $42.83 gCO_{2eq}MJ_{PB}^{-1}$ for the emissions associated with the analysed system (E_{SC}), as calculated according to equation (2). As shown in Fig. 5, such a value resulted from accounting for each subsystem's contribution, as well as for the benefits related to conservation agriculture practices (NT and organic farming). The latter enabled, indeed, carbon sequestration and subsequent saving of CO_2 . From the figure, there is also evidence that tritello is the greatest contributor to GWP_{100} : contributions from the other feedstock-crop pathways are largely lower compared to tritello and, however, more or less comparable amongst them. For contrast, as regards animal effluents, no contribution was accounted for in SS1, because a zero-burden approach was assumed to model their usage.

Fig. 5. Single source contribution to the GWP_{100} associated with the whole system investigated

Additionally, from Table 8 it appears that for all feedstock pathways, with exception of animal effluents, the highest contribution to GWP_{100} comes from biomass production due to the ammonium nitrate production. In particular, the highest value was recorded for tritello, being equal to $33.228 \text{ gCO}_{2\text{eq}}\text{MJ}_{\text{PB}}^{-1}$. Tritello is the feedstock most contributing to the emissions associated with the plant, due to the low yields in the milling phase (4.5%) and in the net-production of DW grains ($4,050 \text{ kg ha}^{-1}$). As a consequence, a huge amount of those grains is required ($26.88 \text{ kg m}^3_{\text{PB}}$) for production of the amount of tritello ($1.21 \text{ kg m}^3_{\text{PB}}$) demanded for biogas production. This aspect causes amplification of the impact from ammonium nitrate production and administration.

As regards the merits of the transport system (SS2), comparable values were obtained for all feedstock pathways, namely 0.316, 0.203, 0.280 and $0.356 \text{ gCO}_{2\text{eq}}\text{MJ}_{\text{PB}}^{-1}$.

Finally, from calculation the emissions associated with SS3 (processing) resulted to be 5.462, 4.675, 4.423 and $4.641 \text{ gCO}_{2\text{eq}}\text{MJ}_{\text{PB}}^{-1}$ for maize, triticale, tritello and animal effluents. It should be observed that those values are quite comparable, mainly because:

- both electricity and heat self-consumption values are not dependent upon the single feedstock utilised;
- the LHV and the weighting factors (S_n), as reported in Table 7, are quite comparable amongst the feedstocks considered.

Table 8

Weighted E_{SC} associated with all the three subsystems as well as the materials and processes comprised by the system analysed. Values per single feedstock

As per CO_2 -saving, from the related amount indicated in Table 8 there is evidence that it positively affects the value resulting for E_{SC} . In this context, as already clarified, NT and organic farming enables SOC accumulation, so contributing to increased physical, chemical and biological quality of the soil. Therefore, if they were not practiced, higher GHG-emissions would have been recorded for the whole SC with the subsequent decrease in the emission saving. This emphasises upon the importance of conservation cropping systems for enhanced environmental sustainability in agriculture and so in the bioenergy field. In particular, the highest benefit was observed for tritello because, compared to the other feedstock crops it is characterised by the lowest production yield

per ha of cultivated land. This aspect leads to a higher land occupation for DW production compared to the other crops and so to higher carbon savings.

E_{SC} was then allocated to PB [$E_{SC(PB)}$] and the of value of $39.43 \text{ gCO}_{2eq}\text{MJ}^{-1}_{PB}$ was calculated and subsequently added to the emissions resulting from un-combusted methane losses ($4.987 \text{ gCO}_{2eq}\text{MJ}^{-1}_{PB}$), thus obtaining the total value of $44.41 \text{ gCO}_{2eq}\text{MJ}^{-1}_{PB}$. The latter was used for EC_{el} estimation, based upon the electrical efficiency indicated in section 2.1, so finding the value of $121.79 \text{ gCO}_{2eq}\text{MJ}_e^{-1}$.

Therefore, GHG-saving for electricity was calculated following equation (5) resulted in 34.52%, using the FFC established by the latest SWD(2014)259, as already anticipated in section 2.2.1.1. There is evidence that the calculated saving is slightly lower than the corresponding minimum established by the RED and equal to 35%. Apart from the peculiarities of the SC investigated, this result is affected by the values used as FFC: indeed, two alternative scenarios could be considered and assessed. In scenario 1, the FFC originally contained in the RED was considered ($198 \text{ gCO}_{2eq}\text{MJ}_e^{-1}$) and an almost 38% saving was recorded subsequently. Therefore, it should be observed that in this case the plant would satisfy the sustainability target established by the Directive. For contrast, in scenario 2 the FFC was calculated using the EF_{el} extrapolated from Ecoinvent, equal to $641 \text{ gCO}_{2eq}\text{kWh}_e^{-1}$. This value refers to all energy sources and so was corrected considering only the energy share produced from fossil fuels, thus neglecting Renewable and Nuclear Energy sources (RNE). The latter, based upon a Cumulative Energy Demand (CED) analysis performed on the Ecoinvent model ("Electricity, low voltage, at grid, IT"), resulted as the 18.91% of the total of energy sources. As regards the fossil fuel mix considered, it provides the use of the following primary-energy resources (in ground): gas natural (57%); crude oil (23%); and, hard coal (20%). Then, from the aforementioned RNE-percentage a value of $519.79 \text{ gCO}_{2eq}\text{kWh}_e^{-1}$, corresponding to $144 \text{ gCO}_{2eq}\text{MJ}_e^{-1}$, was obtained for fossil energy sources and subsequently used for the assessment. In this case, emission saving would result in almost 20%, so being largely lower than the limit considered by the Directive. All that stated, it can be asserted that the FFC values highly influence the sustainability threshold of bioenergy SCs, because the more they decrease more improvement efforts are required for those SCs to satisfy the emission saving established by the RED.

For instance, in the particular case usage of urea in replacement of ammonium nitrate could be tested to verify whether it is really an improvement. In this regard, it should be observed that assurances were given by farmers and agronomists about the agronomical feasibility of this proposal. In particular, the latter was applied for cultivation of all crops considering the related N-requirements and also the differences existing in N-content terms between the two fertilising products (35% for ammonium nitrate and 46% for urea). From calculation, low amounts of urea were observed per single feedstock-crop compared to ammonium nitrate, thus resulting in both reduced diesel consumption and GHG-emission coming from administration operations. In this regard, Table 9 shows the administered amounts of ammonium nitrate and urea per single feedstock crop, as provided by the farm.

Table 9

Comparison of administered amounts (kg ha^{-1}) of ammonium nitrate and urea per single crop

From application of the solution proposed, EC_{el} would be reduced by a total of 54.53% compared to the initial study ($121.79 \text{ gCO}_{2\text{eq}}\text{MJ}_e^{-1}$) and the related saving would increase to 70.22%. Focussing attention upon the weighted value of E_{SC} per single feedstock-crop (Fig.6), there is evidence that the greatest reduction was observed for tritello due to the lower production yield of DW compared to maize and tritcale.

Fig. 6. Comparative assessment related to the use of urea in replacement of ammonium nitrate for all feedstock crops

Hence, based upon the obtained results the solution proposed could be taken into real consideration for enhancement of the sustainability of the analysed SC so as to largely satisfy the RED requirements.

4. Conclusions

The present study fulfilled the objective defined and in fact enabled assessment of the GWP_{100} and subsequent quantification of the GHG-emission saving. The assessment documented that the plant is very close to satisfying the minimum limit established by

the RED and so improvements are needed. In particular, the analysis highlighted that for enhancement of the environmental sustainability associated with the SC in question it would be enough to replace ammonium nitrate with urea. Indeed, the GHG-emission saving would increase from 34.52% to 70.22%, thus largely satisfying the RED limit. In addition, the study highlighted that conservation practices, such as NT, can significantly enable reduction of the GHG-emissions coming from agricultural activities. Therefore, those practices should be increasingly adopted for cultivation of energy crops, because the latter significantly contribute to biogas production yield enhancement. Furthermore, the GWP₁₀₀ resulted to be so highly influenced by the choice of the FFC, that in one case the related value was largely lower than the minimum required. In particular, it should be observed that FFC reductions lead to greater efforts (by farmers and producers) for agro-biogas SCs' environmental sustainability enhancement and subsequent compliance with the RED. Finally, the procedure applied in this paper for GHG-emission estimation could be considered as the starting point for development of a standardised method designed for assessing agro-biogas SC environmental sustainability in the frame of the RED, allowing for the use of both primary and background data. Therefore, the authors believe that it could be useful for those researchers involved in the assessment of bioenergy systems who frequently utilise the Ecoinvent database systems for development of LCA-based studies. In this way, they have series of available background data whose elaboration can facilitate application of the RED methodology.

Acronym

- CAP: Common Agriculture Policy;
- CCGT: Combined cycle gas turbine;
- CED: Cumulative Energy Demand;
- CHP: Combined Heat and Power;
- DW: Durum Wheat;
- EC: European Commission;
- EF: Emission Factor;
- EU: European Union;
- FFC: Fossil Fuel Comparator;

- FQD: Fuel Quality Directive;
- GHG: Greenhouse Gas;
- GWP₁₀₀: 100-year Global Warming Potential;
- IGCC: Integrated gasification combined cycle;
- ILUC: Indirect Land Use Change;
- IPCC: Intergovernmental Panel on Climate Change;
- LCA: Life Cycle Assessment;
- LF: (Digestate) Liquid Fraction;
- LHV: Low Heating Value;
- LNG: Liquefied natural gas;
- NT: No-Tillage;
- PB: Purified Biogas;
- RNE: Renewable and Nuclear Energy;
- RED: Renewable Energy Directive;
- SC: Supply Chain;
- SF: (Digestate) Solid Fraction;
- SOC: Soil Organic Carbon;
- SS: Subsystem;
- SWD: Staff Working Document.

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Table 1

Feedstock	$Y_{n(PB)}$ $m_{PB}^3 kg_{VS}^{-1}$	VS_n $kg_{VS} kg_n^{-1}$	$1/(Y_n * VS_n)$ $kg_n (m^3_{PB})^{-1}$	$LHV_{PB(n)}$ $MJ (m^3)^{-1}$	$P_{n(PB)}$ $MJ kg_n^{-1}$
Maize	0.710	0.342	4.120	19.03	4.619
Triticale	0.759	0.285	4.625	19.03	4.192
Tritello (as biowaste)	0.846	0.238	4.969	21.54	3.974
Animal effluents	0.446	0.066	33.999	18.31	0.612

Table 2

CROP	M _d kg(M _d)kg _n ⁻¹	EF _{M_dP} gCO _{2eq} kg(M _d) ⁻¹
SEEDS		
Triticale	8.89E-3	335.43
Maize	3.077E-4	1,783.00
DW	4.938E-2	2,043.00
AMMONIUM NITRATE		
Triticale	2.22E-3	8,487.00
Maize	6.838E-3	
DW	7.407E-2	
GLYPHOSATE AND OTHER HERBICIDES		
Triticale	---	---
Maize	1.966E-5	10,349.00
DW	1.235E-4	10,021.00
FUNGICIDES		
Triticale	---	---
Maize	---	---
DW	2.47E-4	10,437.00

Table 3

CROP	$D_{agr.act}$ $kg(D_{agr.act})kg_n^{-1}$	$EF_{D_{agr.act}}$ $gCO_{2eq} MJ^{-1}$
SEEDING		
Triticale	9.111E-4	86.23
Maize	3.504E-4	
DW	6.173E-3	
CHOPPING/HARVESTING		
Triticale	2.346E-3	86.35
Maize	9.026E-4	
DW	8.222E-3	
MINERAL FERTILISATION		
Triticale	1.176E-4	88.41
Maize	4.521E-5	
DW	1.620E-3	
ORGANIC FERTILISATION (DSF AND DLF SPREADING)		
Triticale	7.778E-5	85.93
Maize	2.393E-4	
DW	---	
FUNGICIDE AND HERBICIDE ADMINISTRATION		
Triticale	---	85.77
Maize	7.008E-5	
DW	3.233E-3	
IRRIGATION		
Triticale	---	85.65
Maize	1.320E-3	
DW	---	

Table 4

CROP	$e_{N_2O(D)}$	$e_{N_2O(IND)}$	$e_{N_2O(Tot)}$
	$kg\,ha^{-1}$		
Triticale	0.485	0.035	0.520
Maize	3.113	0.280	3.393
DW	1.082	0.105	1.187

Table 5

CROP	D_{M_dT} kgk_n^{-1}
SEEDS	
Triticale	2.204E-4
Maize	1.065E-4
DW	5.926E-5
AMMONIUM NITRATE	
Triticale	2.889E-5
Maize	4.582E-5
DW	4.543E-4
GLYPHOSATE AND OTHER HERBICIDES	
Triticale	---
Maize	1.504E-6
DW	1.482E-5
FUNGICIDES	
Triticale	---
Maize	---
DW	3.062E-5
DSF/DLF	
Triticale	4.831E-4
Maize	1.115E-3
DW	---

Table 6

CROP	D_{M_dT} $kg(m^3_{PB})^{-1}$
Triticale	1.30E-3
Maize	1.02E-3
Tritello	3.19E-4
Animal effluents	1.12E-2

Table 7

Weighting	I_n ($t_n y^{-1}$)	AM_n	SM_n	W_n	$P_{n(PB)} * W_n$ ($MJ\ kg_n^{-1}$)	$S_{n(PB)}$
Maize	0.121	0.660	0.650	4.619	0.561	0.294
Triticale	0.117	0.720	0.700	4.192	0.489	0.256
Tritello	0.119	0.160	0.150	3.974	0.471	0.247
Animal effluents	0.630	0.900	0.900	0.612	0.386	0.202

Table 8

Subsystem (SS)	Phase	Materials and processes	Weighted E_{SC} ($gCO_{2eq}MJ_{PB}^{-1}$)			
			Maize	Triticale	Tritello	Animal effluents
SS1 Biomass production	Crop cultivation	Seeds	0.030	0.016	0.053	
		Input-material production				
		Ammonium nitrate	3.141	0.980	33.228	
		Glyphosate and other herbicides	0.011	0	0.007	
		Fungicides	0	0	0.136	
		Seeding	0.070	0.176	1.210	
		Chopping/harvesting	0.181	0.453	1.614	
		Mineral fertilisation	0.009	0.023	0.326	
		Agricultural activities				
		Organic fertilisation	0.048	0	0	
		Fungicide and herbicide administration	0.014	0	0.630	
	Tritello production (durum wheat grain milling)	Irrigation	0.263	0	0	
		Direct and indirect N_2O emissions from soil	1.101E-06	3.792E-07	5.431E-06	
		Total emissions from crop cultivation	3.768	1.662	37.201	
		Maize and triticale ensilage	0.053	0.052	0.000	
		Electricity	0	0	2.832	
		Heat (from natural gas)	0	0	1.370	
		EMISSIONS FROM SS1	3.820	1.714	41.405	
SS2 Transport		Input material to cropland	0.265	0.147	0.114	
		Durum wheat grain to milling plant			0.153	
		Feedstock to anaerobic digestion plant	0.052	0.056	0.013	0.356
		EMISSIONS FROM SS2	0.316	0.203	0.280	0.356
SS3 Processing		EMISSIONS FROM SS3	5.462	4.675	4.423	4.641
Emissions from all subsystems			9.599	6.592	46.108	4.997
Carbon savings			-1.410	-3.169	-19.884	0
Resulting total emissions [$E_{SC(n)}$]			8.189	3.423	26.224	4.997
E_{SC}			42.834			

Table 9

Feedstock crop	Mineral fertilisation product	
	<i>Ammonium nitrate</i>	<i>Urea</i>
<i>Maize</i>	400	305
<i>Durum wheat</i>	300	230
<i>Triticale</i>	50	38

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6