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Is Bioenergy Truly Sustainable When Land-Use-Change (LUC) Emissions Are Accounted for? The Case-Study of Biogas from Agricultural Biomass in Emilia-Romagna Region, Italy

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Abstract: Bioenergies are considered sustainable alternatives to fossil energy sources in the European Union (EU) renewable energy targets for 2030. However, their performances in terms of greenhouse gases (GHG) savings may be affected by indirect emissions related to the required land-use-change (LUC) that should be taken into account when modelling their sustainability. The European Renewable Energy Directive (RED) introduced a number of GHG emission criteria, in comparison with fossil fuels, that bioenergy deriving from agricultural biomasses must comply with. The Emilia-Romagna region (North-Eastern Italy), the second largest Italian biogas producer, has recently issued its Regional Energy Plan (REP), which set an ambitious increase of about 40% of the current installed electric power from biogas up to 2030. The aim of this study is to assess the sustainability of Emilia-Romagna REP accounting for the required indirect land-use-change (ILUC), due to the bioenergy crop expansion, potentially needed to reach the targets. Based on regional data available on biogas production, the amount of land used for maize silage to be destined to biogas production (as a model agricultural feedstock) has been calculated for the actual state-of-the art and towards 2030 scenarios provided by the REP. Starting from average GHG emissions associated with biogas production from 100% maize silage of 35 gCO_2 eq/MJ, a further contribution of 8–18.5 gCO_2 eq/MJ due to LUC has been found. Our findings indicate that it is difficult to assess the global GHG savings from the bioenergy targets fixed by regional energy plans when LUC effects are considered. Careful analysis is necessary in each case to avoid creating negative impacts.

Keywords: biogas; indirect land-use-change; energy planning; renewable energy sources; agricultural biomass; energy crops

1. Introduction

One of the ways to cope with the greenhouse effect, and the consequent climate change caused by the global extensive use of fossil fuels, is to close the carbon cycle in nature by the use of renewable fuels. The latter enables the recycling of sources of biological origin by energy production and consumption of the resulting carbon release by photosynthesis [1]. Such biofuels are principally biogas (a mixture of methane and carbon dioxide) generated by anaerobic digestion of organic feedstock and waste, ethanol, produced by fermentation of carbohydrates, and biodiesel, produced by transesterification of lipids [2]. They are usually classified in first to fourth generation depending on the source from which the biofuel is derived [3]. In addition, a new generation of biofuels, including bio-hydrogen [4], gamma valerolactone (GVL) [5], alkyl levulinates [6] and alkyl valerates [7] has been gaining a growing interest.

There is no question that in certain cases biofuels can be deployed in highly beneficial ways. There are, however, significant parts of currently used biofuels' mix that do not contribute substantially to either climate protection or reduced oil demand. The problem is a complex one of scale and timing: some biofuels replace oil and reduce CO_2 emissions, but as production reaches wider scales the associated social, environmental, and financial costs can far outweigh any potential benefits [8].

Although analyzing the sustainability of biofuels production began as an academic exercise, it has been becoming a mandatory requirement for policy makers. "Sustainability" as it is applied to biofuel production and consumption has not been unanimously defined. However, a common core concept is that sustainable capacity of the natural resources on which it is based, is economically feasible and it is socially and environmentally acceptable [9].

For example, despite many advantages of biodiesel, it is now widely recognized that its widespread use raises some sustainability issues. Vegetable oils can be imported to Europe as it is practiced today, but this way the impacts of their production are shifted elsewhere in the world, where environmentally compliant manner for such development and its control can be questionable [10]. For example, the rapid expansion of bioethanol production from sugarcane in Brazil has raised a number of questions regarding its negative consequences and sustainability. On the one hand, there are positive impacts of bioethanol in reducing the emission of air pollutants and helping to close the carbon cycle due to its vegetal origin, but on the other hand, potential negative impacts such as future destruction or damage of high-biodiversity areas, deforestation, degradation or damaging of soils through the use of chemicals and soil decarbonization, water resources contamination or depletion have been recently highlighted [11].

In this regard, the European Union (EU) has adopted the Renewable Energy Directive 2009/28/EC (RED) and recently the next 2018/2001/EC (RED II), that committed measurable targets for fuel demand in road transport [12]. As already introduced in the original RED, the RED II confirms a series of greenhouse gas (GHG) emission criteria that biofuels must comply with to be counted as such [13]. As shown in Figure 1, taking as references the average emission related to fossil fuels (83.8 gCO_2eq/MJ), the RED and RED II provide different reduced thresholds, that is at least 60% less GHG for biofuels in plants starting to operate after 2015, whereas for installations in-use before that date, 50% of reduction is required.

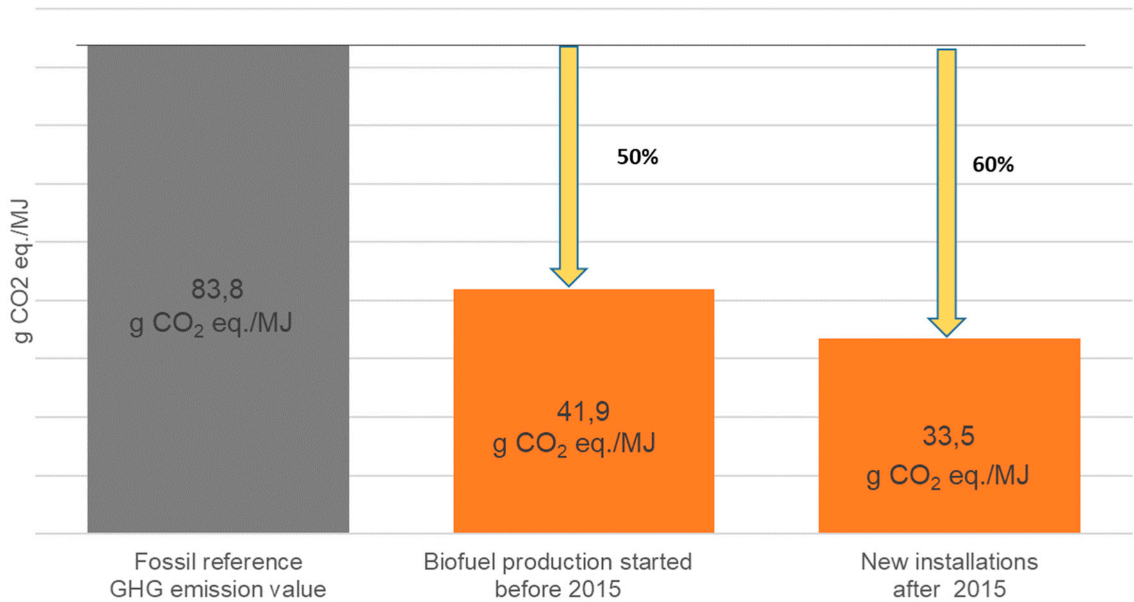

Figure 1. Maximum greenhouse gases (GHG) emission thresholds based on RED environmental sustainability criteria for biofuels production. Value for fossil fuel reference comes from the RED. Currently no other values can be applied.

Among biofuels, biogas is considered to be a fundamental player at European level in achieving these energy targets, because of its versatility and its capacity to be stored, which makes it suitable for a wide range of applications (heating, transportation and electricity production) [14]. In the last two decades, EU biogas production has increased about eightfold.

In fact, biogas can be transformed into electric energy, or biofuel after carbon dioxide removal, and can be produced starting from agricultural biomass, animal manure and a variety of agri-food wastes [15–17]. In particular, energy crops (maize, grasses, beets, sunflowers, etc.) are used in large quantity because they can stabilize the anaerobic digestion process, and are easily provided in agricultural-based economy regions [18]. However, this introduces concerns about the potential adverse impacts on food security and environmental repercussion of intensive agricultural production for bioenergy instead of food purposes. Several studies on environmental sustainability and advantages of biogas production plants using a life cycle assessment (LCA) approach have been recently published. In these studies, [19–21], biogas production from different organic substrates (in mono and co-digestion) and its possible uses have been set up from the environmental and energy perspectives, with special attention to GHG emissions as alternative to fossil fuel. Despite shared opinions on biogas as a form of renewable energy with reduced carbon footprint [22], it has been already reported by several authors [23,24] that anaerobic digestion of raw materials derived from dedicated crops will not necessarily lead to sustainable practices. In fact, the biomass cultivation could cause significant environmental impacts on global warming, acidification and eutrophication potential. Moreover, the land-use change (LUC) effect and the consequent indirect CO_2 emissions caused by the increase in energy crops demand are very rarely taken into account in LCA calculations [25]. Even when they are, conclusions are often contradictory or confusing, since these effects depend on the initial carbon stock, land use types and management and the specific climatic region [26]. On the other hand, it is today widely recognized that LUC is one of the drivers of global environmental change, leading to alterations in soil organic carbon content, and changes to several ecosystem services, potentially increasing GHG emissions [27]. More in detail, LUC can be classified as direct LUC (or DLUC) and indirect LUC (or ILUC). DLUC takes place when energy crops production removes cropland from food production in one country, this indirectly causes changes to GHG release elsewhere, for instance when native habitat is converted to cropland to compensate for the lack of food production, thus generating ILUC [28]. Figure 2 better shows the differences between DLUC and ILUC, representing as Region 1 the region where biofuel is produced from energy crops and used, and as Region 2 a region of the world where additional crop is produced to supply the lack of human food/cattle feed production in Region 1. In Figure 2a no energy crops are cultivated, as baseline. In Figure 2b, Region 2 is not affected by energy crops extra-production because all effects burden on Region 1 (i.e., forests are converted to cropland for energy crops production, generating DLUC effect). In Figure 2c, Region 2 becomes a human food/cattle feed exporting region towards Region 1, because Region 1 converted lands to human food/cattle feed production to produce energy crops, generating ILUC effect. Whereas DLUC due to increased demand of bioenergy has been debated starting from the early 1990s [29], the discussion on ILUC has only recently arisen [30].

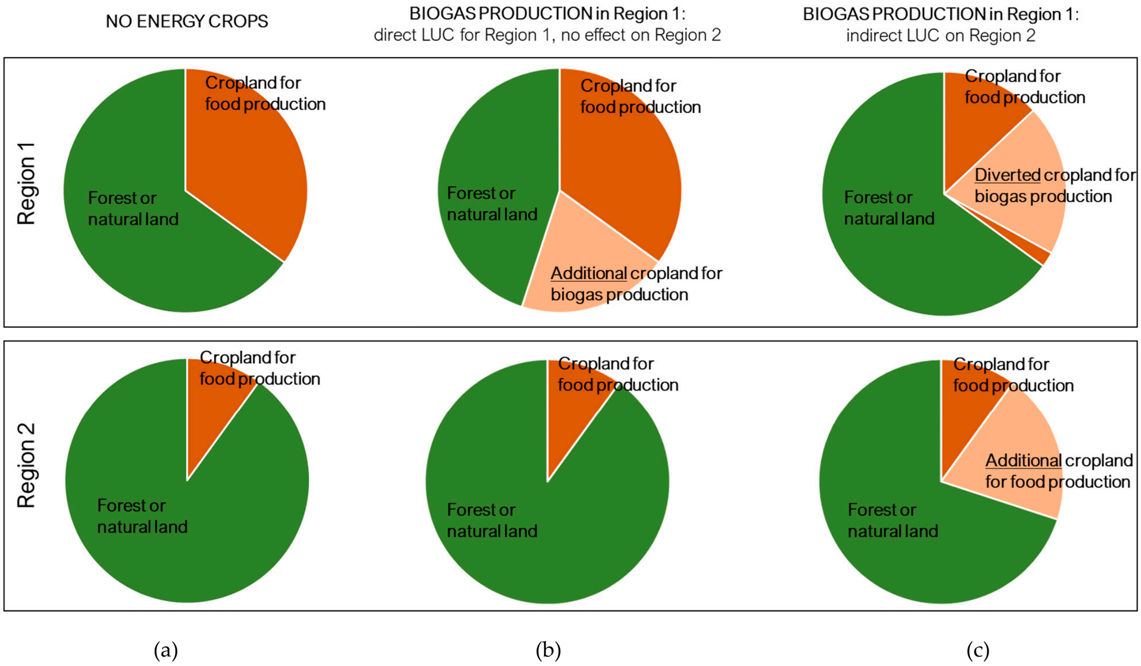

Figure 2. Direct versus indirect land-use-change (DLUC vs ILUC) derived from biogas production in Region 1, in comparison with no biogas production from energy crops (**a**). When additional cropland for energy crops is diverted to forest or natural land in the same region of biogas production (Region 1), the effect is DLUC (**b**). When energy crop is cultivated in existing cropland in Region 1 and, as a consequence, food/feed is supplied by land diversion in Region 2, the effect is ILUC (**c**).

Nevertheless, the LUC effect, both as DLUC and ILUC, could sometimes completely alter the overall sustainability assessment of a process [31].

In particular, whilst DLUC can be measured, one of the principal difficult when ILUC is included in GHG balance calculations is the uncertainty of estimation. In fact, ILUC cannot be directly observed or measured, but so far only modelled at global level with approximate and complex algorithms [32]. ILUC is essentially intangible, so nowadays there is as yet no empirical evidence of land-use-change, as it would depend on detailed tracing of money, land use and agricultural products.

Various models have been used to estimate the ILUC impacts of biofuel production, some based on global agro-economic equilibrium, as the impact model proposed by the International Food Policy Research Institute (IFPRI) and used for assessing the land-use-change consequences of EU bioethanol and biodiesel [33]. Other models use a causal-descriptive approach, where a causal chain of events following the additional production of biofuels is constructed based on historical data, as IMAGE (Integrated Model to Assess the Global Environment) model developed by The Netherlands Environmental Assessment Agency (PBL) [34], or the CSAM (Cropland Spatial Allocation Model) model developed by the EU-Joint Research Centre (JRC) [35].

A wheat-growing farmer in Europe will not see any indirect effects on his actions, and it can never be proven that a certain land use in Brazil, for example, is the effect of European farmer's change from producing wheat for food to wheat for ethanol. The links are complex and impossible to attribute to a certain field. Most models calculate ILUC on a hectare base, then attribute a GHG emissions factor for LUC and finally allocate the emissions over a number of years (usually 20 years) and per unit of energy of fuel [36].

As reported in some cases of biodiesel or bioethanol production, it has already been demonstrated that ILUC could increase GHG emissions to such a level that the biofuel overall GHG emissions were higher than those of the corresponding fossil alternative [37]. Therefore, the need to estimate the specific effects of LUC derived also for agricultural biogas has been considered particularly cogent in the bioenergy sector.

In Europe, biogas production is principally concentrated in Germany, Denmark, Austria, Sweden and Italy [38]. Drawing attention to Italy, although the strong public incentives policies for electricity production from biogas have been lately revised [39], the interest in biogas production from agricultural biomass is still growing. Due to the continuous decrease of income from food crops, conversion to energy crops has become an attractive business opportunity for farmers [40]. Moreover, growing energy crops for fuel production on the farm can be cost more effective than producing food crops [41]. A study by Hélaine et al. [42] focuses on the impact of EU biofuel policies on European commodity prices. They quantify the change in commodity prices resulting from abandoning the EU biofuel consumption targets in 2020. They find that compared to a *business-as-usual* scenario, most of the feedstock prices decline by 5 percent at most, with the exception of the EU price of vegetable oils which would decrease by 48 percent. The authors also simulate that with no biofuel policy in the European Union, almost 6 million hectares less cereals, oilseeds, sugar crops, and palm oil would be harvested globally.

Today, Italy is the second largest producer of agricultural biogas in Europe, with about 1200 biogas plants based on agricultural feedstock, which correspond to about 80% of all plants now operating in Italy [43]. In Italy, the energy policy is managed as a concurrent responsibility between the state and the regions, and regions have major administrative and planning decision making power on this matter. Consequently, regions can adopt separate policy instruments and energy systems, depending on the specific regional energy needs and natural resources available. The Emilia-Romagna region, the second Italian largest biogas producer, has recently issued its Regional Energy Plan (REP), setting the strategy and targets for energy, bioenergy and climate up to 2030 [44]. In the REP, a significant contribution of energy from biogas has been allocated towards 2030, increasing the 2014 level of 234 Megawatts (MW) of installed electric power from biogas, to 298 MW in the viable scenario, or 320 MW in the most optimistic one [45].

The aim of this work is to use Emilia-Romagna as a case study to analyze the current existing data on carbon dioxide emissions of local maize-silage biogas plants (referring to *standardized biogas plant* data), to calculate the actual and the towards 2030 land coverage necessary to sustain the declared biogas production targets, and the corresponding LUC emissions, in order to assess the overall sustainability of REP targets in terms of agricultural biomass-based biogas production. Italy has the second strongest agricultural sector in Europe and the Emilia-Romagna Region is one of the leading agricultural regions in Italy, so the case of Emilia-Romagna region, taken as a model to carry out the study, may provide evidences of wider interest of what is taking place at the global scale with respect to the use of energy crops for biofuels.

Thus, our aim is to better understand the amount of GHG emissions from maize-silage area expansion in the region (DLUC), or elsewhere (ILUC) would be assigned to energy crops for biogas. In other words, to understand how much ILUC would be attributed to 1 megajoule (MJ) of biogas if a portion of land had been diverted for that use, adapting the existing global agro-economic models to a regional scale.

To the authors' best knowledge, this is the first attempt to apply and validate at Italian local level the EU guidelines on DLUC/ILUC calculation.

2. Methodology, Case Study and Model Development

2.1. The Case-Study Area

Emilia-Romagna is a region located in the North-East of Italy, with a territory of 2,245,300 ha. The regional territory is about 48% plane and hosts the biggest and most fertile plain in Italy (southern part of the Po' Valley). The rest of the land is split in hilly areas (27.1%) and mountain areas (25.1%). Agriculture accounts for 3.4% of the regional economy, compared with 2.8% at national level. The utilized agricultural area (UAA) accounts for about 50% of the territory (Figure 3). Of these, cereals production covers more than 30%, wheat and maize in particular, while other crops show just marginal percentages [46].

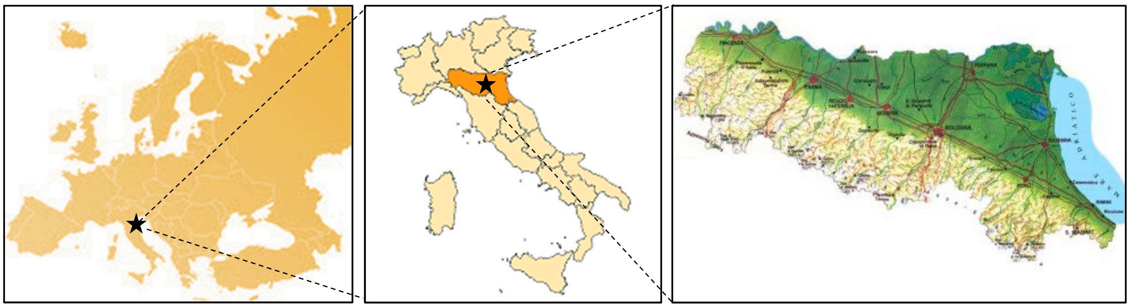

Figure 3. Localization of Emilia-Romagna region in the North of Italy, Europe. Green represents the flat arable land, whereas the light brown the hilly and mountain areas.

2.2. Current Regional Biogas Plants Recognition

The region of Emilia-Romagna, as a result of national incentives policy, has been subjected to a rapid increase in biogas production. Currently, 215 plants are registered, with a total energy supply of 170 MW. 184 are supplied with agricultural, zoo-technical and agri-food waste resources, with a total installed electric power of 138 MW, the remaining are supplied with organic fraction of municipal solid waste (OFMSW) or landfill gas [47]. The latter have been excluded from this analysis, because they do not have any direct or indirect influence on land-use and land-use change.

Based on regional surveys and data recorded by local authorities [48–51], among the 184 plants:

- 18 use as feedstock only animal manure and/or slurry (installed electric power per plant < 0.1 MW);
- 48 use as feedstock a very variable mixture of 10–80% of energy crops, 90–10% of animal manure/animal slurry and 0–30% or agri-food waste (installed electric power per plant in the range 0.1–0.4 MW);
- 12 use as feedstock only agri-food waste (installed electric power per plant, 1.0 MW);
- 16 use as feedstock only energy crops (installed electric power per plant, 1.0 MW);
- 23 use as feedstock a mixture of 70–90% of energy crops with integration of animal manure or food waste in small percentages (installed electric power per plant, 1.0 MW).

Unfortunately, detailed information is available only for a limited number of plants (117) because under a declared electric power of 1 MW, they are not subjected to any mandatory certification schemes related to feedstock, unlike plants which produce 1 MW or more (only 5 regional plants declared an installed electric power > 1 MW). Data for spatial distribution of plants were obtained from the cartographic dataset of the Regional Agency for Environmental Protection of Emilia-Romagna (ARPAE) [52].

2.3. Net Land Use and Area Contribution Factors Calculation (ILUC Area)

To assess the impact of land-use-change on biogas feedstock production from agricultural crops, some simplifications have been proposed. A first assumption to discard the ILUC derived from animal manure/animal slurry, as well as for agri-food waste, taking into account that they are both by-product of a main supply chain, on which the overall impact of land use has been already accounted for [53]. Secondly, the overall amount of feedstock required to feed all the 184 plants has been estimated starting from the available information and speculating on missing data. Based on the average available feedstock recipes, we have extended them to all plants in the region of the same size class. Third, maize silage has been taken as model crop in all simulations, because it is the most widely used as energy crop for biogas production in the region, due to its highest biogas yield per mass unit [54].

To assess the overall regional land use required to produce energy crops (in hectares), now and in view of REP targets up to 2030, we have followed 5 methodological steps:

i. Group plants in 5 installed electric power classes and calculate the overall electric power for each class;
ii. Set an average feedstock recipe for each class, based on available data (as mentioned above) (Table 1);
iii. Calculate the amount of biogas in Nm^3/year based on the lower heating value (LHV) of biomethane and on the average value of biomethane content in biogas from biomass resources;
iv. Estimate the amount of maize silage in tonnes of dry matter required to obtain the calculated amount of biogas from energy crops, based on maize-silage biogas yield;
v. Estimate the land necessary to produce such an amount of maize silage in hectares (*gross land use*).

Table 1. Classes of biogas from renewable resources plants based on size. Feedstock percentages have been obtained averaging and integrating available data. For plants in Classes 4 and 5, three different average feedstock mixes have been reported.

Class	Range of Plant Size (MW)	Total Installed Electric Power (MW)	Feedstock		
			Energy Crops	Animal Manure/Slurry	Agri-Food Waste
1	<0.1	1.1	-	100%	-
2	0.1–0.4	9.8	30%	40%	30%
3	0.4–0.8	5.6	50%	30%	20%
4	0.8–1	24.4 34.2 53.8	- 100% 70%	- - 15%	100% - 15%
5	>1	4.9 2.1 2.8	- 100% 70%	- - -	100% - 30%

Gross land use has been here defined as the amount of land to produce 1 GJ of biogas from maize silage in Italy. In this case, *gross land use* corresponded to *net land use*, being for maize silage 100% product recovery, without any by-product allocation. All reference data used to perform steps iii. to v. have been reported in Table 2.

Table 2. Reference data of biogas from maize silage used in this study. VS = volatile solids.

Parameter	Value	Sources
LHV of biomethane	33 MJ/m^3	[55]
Conversion of maize silage to biogas	9.9 GJ/tonne	[55]
Biogas yield	670 Nm^3/kg VS	[56]
Methane content	53%	[56]
Electric energy conversion efficiency	32%	[22]
Average working hours/year	8000	
Yield per hectare (fresh matter)	60 tonne/ha	[57]
Dry matter content	35%	[57]

Methane content and biogas yield values used in this study [56] derived from data published by CRPA (Research Center of Animal Production, Emilia-Romagna, Italy) that is, at regional level, the most credited research center in the field of biogas research and studies, and one of the most recognized in Italy. Data regarding maize-silage yield per hectare and dry matter content are relevant for local production.

Using the approach suggested by the European JRC [53], the amount of maize silage to feed the current and future biogas plants has been considered to come partly through yield increase on the same lands, and partly from area expansion. To estimate the area expansion contribution, the following factors have been calculated:

i. the *local factor*, assuming that maize production takes place in the same region where maize is diverted to maize silage for biogas. For EU27, the local factor has been estimated by JRC as 0.08.
ii. the *exporting regions factor*, assuming that the extra crop production occurs in the world regions that export maize to Italy. In this case, the area contribution factor is the average of maize exporting regions weighted by their share of net imports to Italy, based on the following equation:

$$C = \sum_i A_i \cdot B_i \cdot y_i \quad (1)$$

where C is the area contribution factor from maize exporting regions, A_i is the share of country i in the total net imports to Italy, B_i is the area expansion component of production increase in a given country, y_i is maize yield factor in a given country. y_i values have been calculated as the ratio between the maize yield in Italy and maize yield in the given country. This adjustment is necessary since the crop yields in a specific country could be different and influence the amount of land necessary. The exporting countries are those that contribute to the area expansion of maize production, assuming that maize is produced in exporting countries according to their share of imports to Italy.

Net land use has been directly multiplied by the area contribution factors (*local* + *exporting regions*) to estimate the ILUC area related to biogas production from maize silage in the Emilia-Romagna region.

2.4. ILUC Emissions Estimation from ILUC Area under the EU-RED Directives

To estimate the emissions due to cropland expansion from ILUC area results, we apply emission factors (tCO_2/ha) given by the IMAGE model developed by the PBL [34] and by CSAM model developed by JRC [35]. Our results were compared with ILUC emissions calculated using the GLOBIOM model developed by the International Institute for Applied Systems Analysis (IIASA), corresponding to 21 gCO_2/MJ of biogas produced by maize silage [55].

The overall methodology set up and applied could be resumed in Figure 4:

Currently, according to the methodology in the RED Directive [58] GHG emissions related to biofuels utilization should be determined using a so-called chain analysis or LCA approach that considers the GHG emissions associated with various production phases in the biofuel production chain. Expressed as a mathematical relation:

$$E = EEC + EP + ETD + EU + EL + ei \quad (2)$$

where E are the total emissions from the use of the biofuel (gCO_2 eq/MJ); EEC are the emissions from the cultivation of raw materials; EP are emissions from biofuel processing; ETD are emissions from transport and distribution of biofuel; EL are the annualized emissions from carbon stock changes caused by DLUC, referring to removal of natural vegetation to create arable land and reduction of soil organic matter as a result of vegetation removal and land management. The term *ei* (not actually present in the original equation in Reference [58]) has been introduced by us to account for the estimated ILUC emissions with the methodology used in this study.

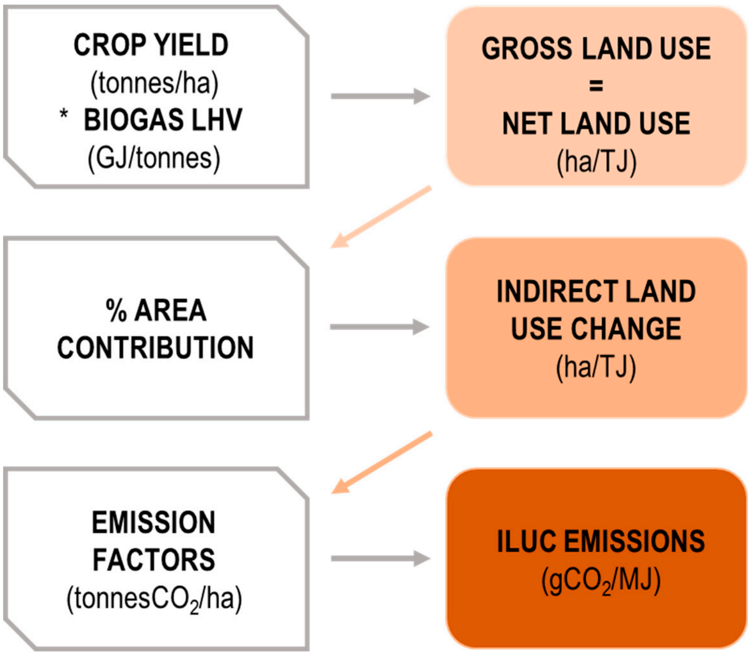

Figure 4. Procedure/phases to estimate ILUC area ILUC emissions (modified from [53]). White boxes show the data used for calculation and the colored boxes the calculated parameter.

2.5. Description of the Examined Cases and Data Acquisition

As *unitary standardized biogas system*, data published by local research institutes [56,59] have been used in this study, referring to a 1 MW conventional plant, fed 100% with local maize silage, operating for 8000 h/year, and located in Northern Italy (Table 3). By comparison, environmental impact as gCO_2/MJ of biogas has been reported also for biogas from agro-food industry byproducts and from agricultural and livestock byproducts. On average, GHG emissions associated with biogas production from 100% maize silage was 35 gCO_2 eq/MJ, taken as reference value for the sum of terms related to emissions due to biogas production EEC + EP + ETD + EU in Equation (2).

Table 3. GHG emissions of unitary standardized biogas system, as reported in [56,59] and taken as reference values for calculations.

Feedstock	gCO_2/MJ
Energy crops (*maize silage, 100%*)	35
Agricultural and livestock byproducts (*maize silage, 8%; sorghum silage, 8%; cow slurry, 30%; cow manure, 30%; pig slurry, 24%*)	25
Agro-food industry byproducts (*maize silage, 8%; sorghum silage, 8%; vegetal orto-fruit waste, 50%; agri-food byproducts, 34%*)	10

3. Results and Discussion

3.1. Net Land Use Calculation for Current Biogas Production from Energy Crops and towards 2030 Scenario

The estimation of the ILUC effect is based on the assumption that land use for biogas would directly or indirectly related to conversion of unproductive lands, diversion from other croplands and/or agricultural yields intensification in the remaining food/feed-devoted lands. The part of the production increase associated with biogas demand caused by worldwide land expansion of displaced crops, is considered to be the ILUC.

As shown in Figure 5, the amount of installed power is not homogeneously distributed in the regional territory. The Eastern part hosts a larger number of plants, including large plants (>1 MW) fed with 100% agri-food waste in proximity to agri-food industries. Small plants (<0.1 MW) are scattered on the territory and mainly associated to livestock types, as usually fed with a mix of manure and crops.

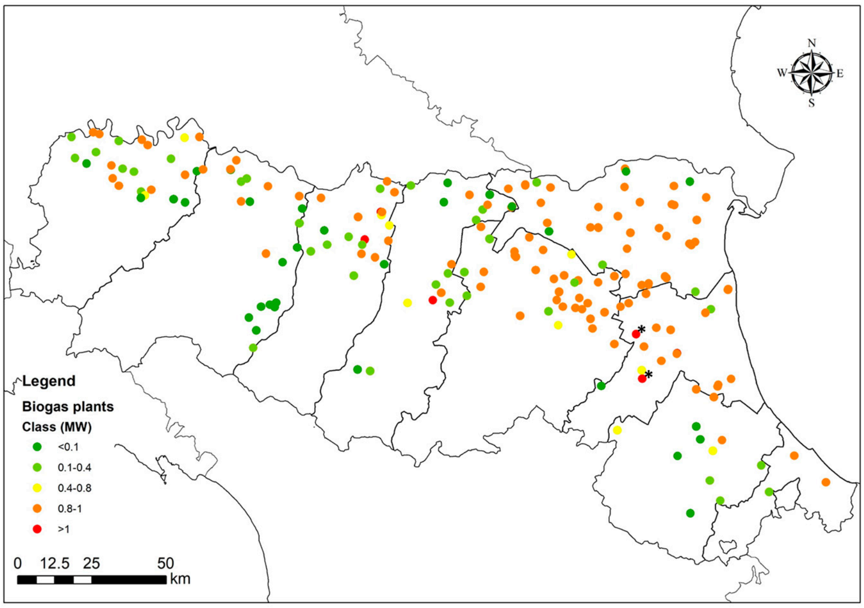

Figure 5. Map of biogas plants power classes, from >0.1 MW to >1 MW. The two asterisks identified plants in red class fed with 100% of agri-food waste, located close to agri-food industries.

Except for those two categories, the majority of other plants are distributed in the overall territory provide energy crops as main feedstock, which is about 60% of the overall biogas produced. Based on Table 1, the total installed power is 138 MW, and according to data reported in Table 2, the amount of biogas produced from energy crops is 81.66 MW, corresponding to about 52,600 Nm^3 of biogas per hour. Following the assumption of considering only maize silage as energy crop and taking into account the different recipes of plants feeding, this leads to an amount of about 630,000 tonnes/year of maize silage dry matter to be supplied. Based on a dry matter yield per hectare of 20 tonnes/ha, 31,500 ha of cultivated land had diverted to bioenergy from human food/cattle feed production in the last decades, corresponding to circa 3% of the entire regional UAA (1,033,000 ha, [59]) and about 10% of the overall regional land cultivated with cereals. It is worthwhile noting that 3% of utilized agricultural area (UAA) is considered the realistic threshold of land use for energy crops production [60]. It is also worthwhile noting that, taking this value as a reference, the actual biogas production has already saturated the local land use considered as sustainable.

Moreover, based on national data [61], from 1982 to 2018 the UAA has been showing a constant decrease of an average of 0.5% per year. In these conditions, a value of about 970,000 ha could be expected for 2030. These data are consistent with the general trend in the EU, where agricultural area has declined by more than 6% since 2000 and is expected to continue the decline further in the period to 2030, mainly at the expense of cereals, permanent grassland and permanent crops, and principally due to urbanization and infrastructure construction in fertile plains [62,63].

As mentioned above, the objectives reported on the REP provided an increase to 298 (viable scenario) or 320 MW (best scenario) of electric power from biogas towards 2030 compared to the level of 234 MW declared for 2014, with a theoretical increase of about 27% and 37% of the installed power, respectively.

In a *business-as-usual* biogas sector development, it implies the necessity of additional 8500 ha in viable case or 11,500 ha in the best case, corresponding to an increase to 3.9% and 4.2%, or worse, if calculated on the basis of the UAA estimated at 2030. In both cases, those values exceed the sustainability threshold.

Net land use gave a value of 4.3 ha/TJ (hectare per terajoule) of biogas from maize silage in the Emilia-Romagna region, corresponding to about 130 ha/MW. This value is in accordance with data reported in Reference [53] of 4.8–5.6 ha/TJ as average of cropland displacement in Europe for biogas from maize silage. In this case, as above reported, gross land use and net land use are superimposed, namely all land can be attributed to biogas, because no allocation of by-product has to be carried out.

With land being a finite resource, this additional contribution has to be unavoidably diverted from soil actually allocated to food/feed production. We are aware that the only changes to be accounted as DLUC are those from one land cover type to another, based on land categories used by IPCC [64], namely a change from forestland to cropland is a land-use-change, while a change from one crop (such as, for example grain, sugar beet or maize for food/feed) to another (maize silage) is not, because variations of soil management, tillage practice or fertilizers input practice are not considered as land-use-change since the soil is still under cultivation as prior to energy crop introduction [65]. This is the reason why usually (as examples, see References [66,67]) the contribution of DLUC (the term EL in Equation (2)) of agricultural biogas is assumed to be zero when energy crops simply substitute other crops. Whereas it has already been demonstrated that DLUC has a dramatic effect on the total GHG emissions of silage maize, which more than double or even triple, if silage maize is cultivated on former grassland or forestland, it is still an open question whether biogas can be used as a bioenergy source without depleting soil carbon stock, due to the lack of long-term data regarding biogas residues effects on soil organic carbon [68]. Some authors reported that, in absence of correct digestate management, the carbon sequestration capacity of soil from food crop to energy crop decreased in the medium-long term [69,70].

Moreover, even though the actual policy excludes to calculate DLUC for cases as the one under investigation, where area expansion from natural land or forestland to cropland is unlikely due to area limitation, and where increase of cropland demand is counterbalanced by crop yield increase, it is worthwhile noting that yield intensification even when it saves land may induce other relevant environmental costs, including off-site impacts of agro-chemicals and fertilizers on natural ecosystems, soil exploitation, loss of biodiversity, leading to an overall loss of ecosystem services provided by soils [71,72]. In fact, as recently reported [73], in Italy the value of ecosystem services provided by area devoted to energy crops is lower than the value of the same area dedicated to food crop.

3.2. Estimation of ILUC Area at Regional Level

As is well-known, ILUC emissions are a controversial subject in discussion on bioenergy sustainability. This study is the first attempt to quantify the indirect effect of energy crops expansion for agricultural biogas at local level. Whereas DLUC has low (or zero) impact for the above mentioned reasons, ILUC should be not negligible, taking into account that Italy is one of the major human food/cattle feed cereal importing countries in Europe, constantly growing [74]. In 2018, maize for human food/cattle feed alone accounted for about 35% of the overall cereals import to Italy, with 4,559,716 tonnes, for a value of about 800 millions of euros. Of course, biogas should not be given all the blame, because it is clearly not the only driver of imports increasing, but undoubtedly the actual 31,500 ha and the future 8500 (or 11,500) ha of loss of human food/cattle feed production contribute to the need of maize supply from abroad, as happens in the case of oil crops for biodiesel or wheat/maize for bioethanol.

As mentioned above, if an extra tonne of biogas feedstock is produced, this increase in production will be covered by a fraction of yield increase and a fraction of land expansion. Overall area expansion is the sum of two contributions, one at local level (estimated by the *local factor*) and one deriving from the land expansion in the exporting countries (estimated by the *exporting regions factor*).

A local area contribution factor of 0.08, corresponding to a portion of 8% of new land from area expansion, calculated at EU27 level, seems an appropriate estimation of land expansion in the Emilia-Romagna region, as well. It reflects the overall scarcity of new lands to convert to cropland in

Europe, where extra agricultural production comes principally from yield increase, in comparison for example to Brazil or Malaysia/Indonesia, where the same indicator has been calculated as a value of 30% and 47%, respectively. It is worthwhile point out that 20 years ago in Europe the same coefficient had a value of 0.26, indicating the progressive strong reduction of natural land or not-cultivated land available for new croplands.

On the other hand, the *exporting regions factor* takes into account the effective impact of ILUC, because leads to an attempt of correlating the diverted land to bioenergy crop in one country with food/feed probably diversion from forestland or grassland in another country, that is basically the main concept of indirect impact related to land-use-change. Data on maize exporting countries to Italy were derived from Reference [75] and used as proxy of regional scale (Table 4), in absence of regional level data available. Over 70% of maize is imported from Europe (France, Hungary, Austria Germany and Croatia) and the remaining 30% is supplied on international markets, principally from Canada, US and Mexico.

Table 4. Reference data on main maize exporting countries to Italy (2015).

Maize Exporting Countries to Italy	Share of Imports to Italy (%) (Term A_i in Equation (1))	Area Expansion Contribution to Export for Maize Crop [53] (Term B_i in Equation (1))	Yield Factor (Term y_i in Equation (1))
France	37	0.054	1.0
Hungary	15	0.160	1.0
Austria	9	0.050	0.8
Germany	9	0.054	1.0
Canada	9	0.627	1.3
US	5	0.627	1.1
Mexico	4	0.160	3.7
Croatia	3	0.160	1.8

The area expansion contributions to export (the third column in Table 4) are those used by JRC [53] and derived from FAOstat export and import data for all regions/countries from Reference [76].

We have assumed that maize is produced in exporting regions according to their share of import to Italy (see Table 4). Based on Equation (1) applied to the first seven countries from where Italy import maize for human food/cattle feed, the *exporting regions* factor has been estimated as 0.19 and used to calculate ILUC area (Table 5). In other words, averaging all contributions, it is as if maize exporting countries to Italy had diverted to cropland a portion of 19% of new land to respond to extra-maize demand in Italy.

Table 5. ILUC area results for current and future scenarios.

	Local Factor	Exporting Regions Factor
Net land use	4.3 ha/TJ	
Area contribution factor	0.08	0.19
Calculated ILUC area	0.35 ha/TJ	0.82 ha/TJ
Total ILUC area	1.17 ha/TJ	

It is worthwhile pointing out that the total ILUC area (1.17 ha/TJ) burdens for 27% of the net land use (4.3 ha/TJ) for energy crop per unit of energy produced. In other words, for each hectare of land used to maize silage for biogas, about 0.3 hectares have to be added to account for ILUC effect. In terms of regional impacts, considering a contribution of 30% due to ILUC area to the current scenario, to the 31,500 ha actually used for maize silage, with respect to the extra-emissions due to ILUC, it is as if a further 9500 ha would be added. Really, 31,500 ha is cultivated to maize silage in Emilia-Romagna, but effective impact burdens on that maize silage is as if 41,000 ha would have cultivated. Similarly, for future scenarios towards 2030, it is as if an extra 3100 (viable scenario) to 3300 (best scenario) would added in the total land count.

3.3. Estimation of ILUC Emissions and Impacts on Current and Fture Regional Biogas Scenario

The immediate consequence is that contribution to GHG emissions of biogas production derived from these extra-land burdens in the overall sustainability balance of biogas production from maize silage.

To estimate the emissions due to ILUC area, the IMAGE and CSAM emission factors for cereals have been applied, as mentioned in the Methodology, Case Study and Model Development section. Both coefficients have been calculated at worldwide level, so they are not region or country-specific. In particular, we have used IMAGE emission factors reported at EU level (93 tonCO_2 eq./ha) and at crop level (102 tonCO_2 eq./ha for cereals) and CSAM emission factor at crop level (226 tonCO_2 eq./ha for cereals) (Table 6). The value spreads depend on the different assumptions of IMAGE and CSAM models, indicating the high grade of variability that still affects these estimations. According to the JRC approach, we preferred to use those models based on a causal-descriptive approach, because they are backed by historical data, making these approaches more transparent and more easily discussed.

Table 6. ILUC emissions estimation (gCO_2 eq./MJ) due to ILUC effect on maize-silage cultivation for biogas production (calculated as product of ILUC area and emission factors). These emissions are spread over 20 years, following the Commission's rules for estimating LUC emissions in the RED annex. This provision is in line with the proposition that a batch of biofuel should achieve the claimed emissions savings within 20 years of consumption [53].

	ILUC Area (ha/TJ Biogas)	Emission Factors (tonCO_2 eq./ha)	ILUC Emissions (gCO_2 eq./MJ)
IMAGE (EU27)		93	5.4
IMAGE (cereals, worldwide)	1.17	102	6.0
CSAM (cereals, worldwide)		226	13.2

The variability in results depending on the model used likely depends on the different assumptions of the two algorithms (for detailed description, please see References [34,35]). The values obtained by IMAGE can be mediated to an average value of 5.7 gCO_2 eq./MJ, whereas the value obtained by applying the CSAM model is more similar to the reference value of 21 gCO_2 eq./MJ as calculated by the GLOBIOM report [53] for ILUC effect on biogas from maize silage caused by area expansion and overall change in soil carbon stock. GLOBIOM is a global model developed with data of over 30 countries from across the world and has been considered as a reference. Probably the lower value calculated at regional level depends on the fact the almost 70% of maize import to Italy derive from Europe, where the contribution to land expansion is low. ILUC emissions are intended as distributed over a 20-year period, as it is common practice in land-use-change modelling, since most LUC emissions take place shortly after the conversion of previously non-agricultural land to agricultural land and it makes little sense to allocate all emissions to the first year after the conversion and to have zero LUC emissions in year two. The twenty-year period is in line with the period used for the allocation of direct land-use-change emissions in the greenhouse gas calculation methodology as laid down in the EU-RED.

As mentioned above, several studies about the GHG emissions and LCA of biogas or biomethane based on energy crops are available in the literature. It has been also widely pointed out that the comparison of the results is rather difficult, as LCA strongly depends on the system boundaries, the technology applied and the assumption taken for the agricultural and technical aspects. In addition, biogas production is related not only to the feedstock used but also to local crops yield and soil characteristics; all data is strongly related to local agriculture management and geographical position. In order to overcome these difficulties and to provide a starting point for researchers and users, local regional authorities created different realistic theoretical standardized biogas plant systems, with their related weighted productive supply chain through bibliographic research and real case studies. At planning level, at territorial and regional scale, it would be extremely important to measure and quantify the environmental impact produced by all biogas plants that work in the territory analyzed, but, as before mentioned, actually it is impossible having all the process data of all single plants. The unitary standardized models here presented represent a "*realistic possible average structure of a biomass energy systems constructed with a good reliability of the bibliographic parameters, that were selected on the base of their scientific and practicality of use*" [58].

Based on Equation (1), the overall impact of biogas production from maize silage in Emilia-Romagna, should provide the contribution of ILUC emissions (the term *ei* in Equation (2)) as addition to the reference 35 gCO_2eq./MJ. Using the IMAGE or CSAM models, it becomes 40.7 gCO_2 eq./MJ or 48.5 gCO_2 eq./MJ, respectively. This confirms that the effective sustainability assessment of biogas from energy crops will change when ILUC contributions are accounted for. Figure 6 shows that biogas from 100% maize silage for plants built after 2015, that are submitted to 60% of GHG savings compared to fossil fuel do not meet the new sustainability criteria, even without considering ILUC contributions, whereas for plants built after 2015 (60% GHG emissions saving threshold), the contribution of ILUC factors makes this situation even worse (Figure 6).

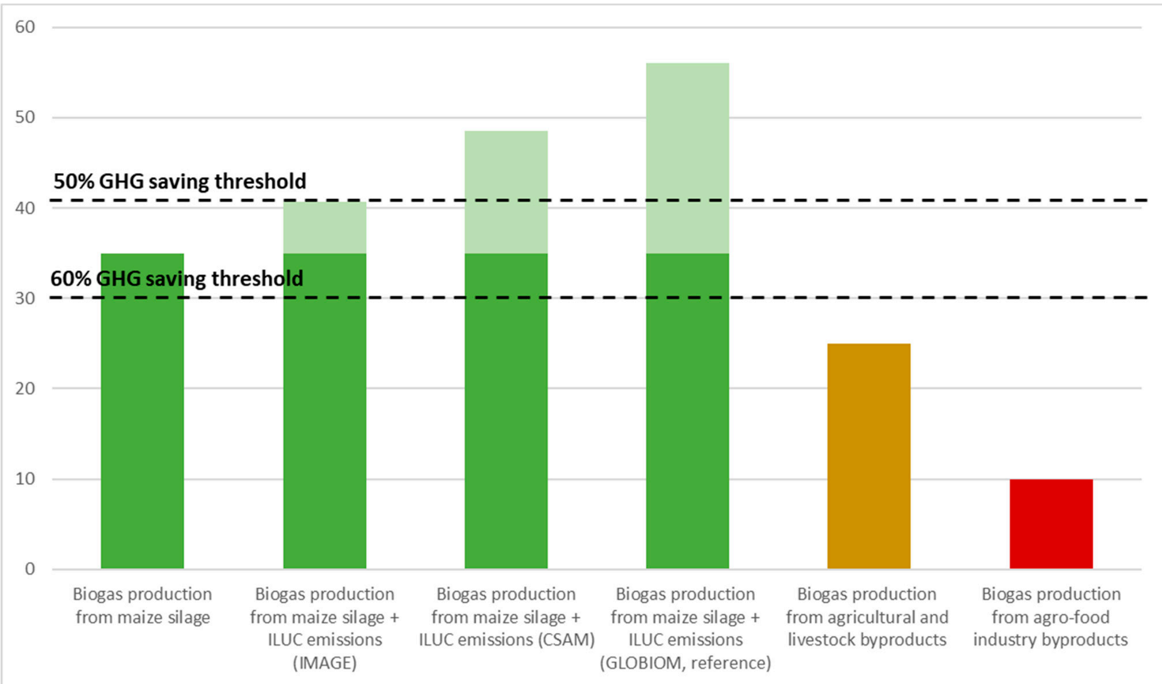

Figure 6. GHG emissions in biogas production from maize silage (dark green) plus ILUC term (light green), calculated with the EU official models, compared with the RED GHG emissions threshold at 50% and 60 %.

As it can be observed, reaching the 2030 targets provided in the regional REP with business-as-usual models and newly-built biogas plants, that is the use of additional 8500 or 11,500 ha for maize-silage cultivation in the next ten years at the expense of other human food/cattle feed crops, will not meet the EU-RED sustainability criteria.

Moreover, based on the results of this study, the actual use of 31,500 ha is generating extra GHG emissions of about 102,500 tonne CO_2 eq. due to ILUC effect, that are not accounted in any GHG balances, while the use of 8500 or 11,500 for maize silage will lead to further 27,200 or 36,800 tonne CO_2 eq. due to ILUC effects. In this study, we have considered maize silage as crop model, because it warrants the highest biogas yield due to its high content of promptly fermentable starch. Other crops, poorer in fermentable sugars and higher in non-digestible fibers could need even more land to supply the requested amount of biomass.

Furthermore, in the present analysis biogas is considered to be on exit from the plant, that is in terms of electric power installed, but, in reality, before being used as biofuel, it has to be upgraded to biomethane through CO_2 removal, with an additional environmental impact [22,77], a contribution that would deserve further analysis. As shown in Figure 6, a possible alternative could be represented by a different biogas plants management, through progressive reduction of dependence on agricultural biomass while improving the use of livestock and agricultural residues, agri-food waste and also OFMSW (data not reported). In those cases, as stated in several studies [78–81], sensible reductions of GHG emissions could be obtained in biogas production and no ILUC effects occur because land use impacts are included in the burden on the main supply chain. Further investigations have to be carried out in order to calculate the impacts of distance from production and utilization sites of residues.

4. Conclusions

Saving GHG emissions and reduction of fossil energy are fundamental concerns in the context of biogas assessment. The opportunity of reducing global warming is closely related to the reduction of GHG emissions. The case of Emilia-Romagna may be a model study, representative of other countries producing biogas from agricultural crops. Biogas can support the targets for biofuels, as reported in the REP towards 2030. However, its environmental sustainability, as defined by the EU-RED, has to be verified, especially in the case of agricultural biomass used as main feedstock due to their potential impacts on land-use-change locally and at global level. The present work focused on the evaluation of GHG emissions of biogas production from a dedicated energy crop (maize silage) when ILUC effects have been taken into account, since DLUC has to be calculated only if land-use-change occurs from one soil category to another.

The main difficulty of this study is the methodology for calculating ILUC, since an endorsed and shared methodology does not yet exist. In fact, the results presented here indicate that the target proposed in the REP to 2030 does not necessarily increase sustainability when energy crops are contributing. Strong commitments will be needed to avoid further soil conversion or some form of limitation regarding ILUC impacts.

Direct and indirect land-use changes undoubtedly burden on bioenergy or biofuel from agriculture and on what should be the right way for achieving the 2030 GHG reduction targets. Accurate measurements that include ILUC in environmental impact evaluations will permit a strong cap to be put on land-based bioenergy and biofuels also beyond 2030, and to provide alternative solutions for biofuels that do not compete for land with food or feed. Any future evaluation on biofuel sustainability should not be limited at local level and should not avoid including the overall consequences at global level, such as ILUC effects. Actually, the results indicate that the target proposed in the REP to 2030 seems to be far from true sustainability when energy crops are contributing, without the inclusion of strong commitments to avoid further soil occupation or some forms of limitation regarding ILUC.

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Abbreviations

ARPAE	Regional Agency For Environmental Protection Of Emilia-Romagna
CSAM	Cropland Spatial Allocation Model
DLUC	Direct Land-Use-Change
GHG	Greenhouse Gases
GLOBIOM	Global Biosphere Management Model
IFPRI	International Food Policy Research Institute
ILUC	Indirect Land-Use-Change
IMAGE	Integrated Model To Assess The Global Environment
IPCC	Intergovernmental Panel On Climate Change
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LHV	Low Heating Value
LUC	Land-Use-Change
MJ	Megajoule
MW	Megawatt
OFMSW	Organic Fraction Of Municipal Solid Waste
PBL	The Netherlands Environmental Assessment Agency
RED	Renewable Energy Directive
REP	Regional Energy Plan
TJ	Terajoule
UAA	Utilized Agricultural Area

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