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Abstract: Anaerobic Digestion (AD) has been recognized as a viable solution to produce renewable energy and to reduce global warming especially when secondary feedstock and/or wastes are used. Several LCA studies analysed the environmental performances of biogas production systems. The results of this review highlight that the goal, scope, life cycle impact assessment (LCIA) methodology, feedstocks and geographical regions covered by the studies vary widely. Most studies are based in Europe, several in China and few in South and North America and in Africa.

To better highlight how the choices on the feeding mix, the digestate storage, the surplus heat valorisation as well as the plant size can affect the environmental performances of agricultural AD plants four plants have been analyzed in this study. The results suggest that the energy crops production and the operation of anaerobic digesters, including digestate emission from open tanks, are the main contributors to the impacts from biogas electricity. This entails that it is environmentally better to have smaller plants using slurry and waste rather than bigger plants fed with energy crops. Recovering heat waste as well as covering of digestate tank would improve significantly the environmental sustainability of biogas electricity, and particularly the global warming category.

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DiSAA

Dear Prof. ***J. Yan***,

Editor-in-Chief of *Applied Energy*

Milan, 4th July 2016

Dear Editor,

We are pleased to enclose the revised version of our original manuscript of our paper entitled "***Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable***" which can hopefully be published in **Applied Energy**.

Many thanks to the reviewers for their comments; they helped us to improve the manuscript.

We hope that the manuscript in the revised form is appropriate for publication in **Applied Energy**.

On behalf of all the Authors, as corresponding Author, yours sincerely,

Jacopo Bacenetti

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Detailed Response to Reviewers
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Ms. Ref. No.: APEN-D-16-03355
Title: Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more sustainable

Dear Editor,
we would like to thank you for the reviewers' comments. We are grateful to all the reviewers for devoting their time to review our manuscript.
As you can see, we have taken most of them into consideration to modify the paper. We hope that the paper in this current revised version can be accepted for publication. Below, we enclose an explanation of how we have addressed the questions raised.

Reviewer #1
The manuscript is working on the review of the environmental impacts of biogas production. It includes good results, an interesting methodology, and related to the scope of this Journal. I suggest to accept it after some minor revisions.

Thank you for your positive comments and for useful suggestions.

The authors should write about the difference between their study and the following research: * Hijazi, O., Munro, S., Zerhusen, B. and Effenberger, M., 2016. Review of life cycle assessment for biogas production in Europe. Renewable and Sustainable Energy Reviews, 54, 1291-300.

Done, we specified in the introduction that the review carried out by Hijazi et al is focused only on European biogas plants and considers an incredibly small number of LCA studies (only 15). In more details, the following sentence has been introduced in the Introduction: "*Hijazi et al (2016) carried out a review focused on agricultural biogas plants in Europe focusing the attention only on the European context and considered in a really small number of LCA studies (only 15).*"

* And finally, there are some comments in the attached word file that authors should consider in the final version. I hope that authors will consider my suggested remarks in the way of manuscript improvement and prepare it to be suitable for publication.

All your suggestions have been taken into account.

Reviewer #2:
(See also attached reviewer's report) A sustainability analysis should have three domains: economic, social and environment. Since this study only deals with environmental issues, I would recommend to include "environmental sustainable" in the title, rather than only "sustainable".

Done, the title has been modified according your suggestion. The new title is: "*Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more <u>environmentally</u> sustainable*"

<u>Abstract</u>
It is a good abstract. However, the two paragraphs seem to be not connected. I suggest describing the reasons of the second analysis (4 case studies) and its relation with the previous review. In addition, the first phrase of the abstract is exactly the same than in the introduction; I would change it in order to make the abstract does not seem like a collage of the rest of the paper.

Following your suggestion, to link the two paragraph the following sentence has been introduced: "*To better highlight how the choices on the feeding mixture, the digestate storage, the surplus heat valorisation as well as the plant size can affect the environmental performances of agricultural AD plants…*".
Finally, the first sentence has been modified and it is now different from the first sentence in the introduction.

<u>Keywords</u>
I suggest adding "review" or "comprehensive review" since it is the main objective of the paper and it is not included in the title.

Done, "comprehensive review" has been introduced among the keywords.

<u>Introduction</u>
The introduction is general clear and well organized. In the first paragraph, when talking about different feedstock available, food waste is differentiated from agricultural feedstocks. However, food waste is not

the only urban substrate available for AD. What happens with sewage sludge? It has been widely used for AD.

It is true, following your suggestion we have specified that also sewage sludge has been widely used for biogas production.

The following references have been introduced:

- Sosnowski, P., Wieczorek, A., & Ledakowicz, S. (2003). Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. Advances in Environmental Research, 7(3), 609-616.
- Murto, M., Björnsson, L., Mattiasson, B. (2004). Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure. Journal of environmental management, 70(2), 101-107.
- Show, K. Y., Lee, D. J., & Tay, J. H. (2012). Anaerobic Digestion of Sewage Sludge. Biological Sludge Minimization and Biomaterials/Bioenergy Recovery Technologies, 319-347.
- Zhang, W., Wei, Q., Wu, S., Qi, D., Li, W., Zuo, Z., Dong, R. (2014). Batch anaerobic co-digestion of pig manure with dewatered sewage sludge under mesophilic conditions. Applied Energy, 128, 175-183.
- Sadhukhan, J. (2014). Distributed and micro-generation from biogas and agricultural application of sewage sludge: Comparative environmental performance analysis using life cycle approaches. Applied Energy, 122, 196-206.

The second and the third paragraphs start with the same idea about "the spread of AD in Europe". I suggest converting them in only one, that speaks about the evolution of AD spread in Europe in relation with the public policies applied.

Done.

I would delate lines 75 and 76.

Done.

Materials and methods
I would suggest explaining better the criteria according to the goals described before. Table 1 is not commented or described and it does not correspond with the review presented in Table 2. If it does not give any useful information, I would delate it.

Thank you for the suggestion, the paragraph has been revised and Table 1 has been removed.

Review results
I would comment/explain the general meaning of Table 2, what is considered in each column, because it is not clear.

Following your suggestion, we expanded (by introducing notes below the Table) the explanations for all the different items considered in the different columns. The whole table has been reconsidered to be more related to the different points discussed in the following sections. General and operational aspects (e.g. location, number of plants considered, size of the plants, etc.) have been anticipated respect to the methodological aspects.

A lot of theoretical information is given in this section. Conversely, the discussion regarding the results of the review is much poor in some cases such as in "type of study". In addition, in "type of study", "functional unit" and "system boundaries" I would explain more in detail the results, given the figures and reasons (for example, the number of studies performing aLCA with respect to the number that carried out cLCA, the reasons why aLCA are in generally more popular, etc).

Following your comment, the results of the review have been deeply discussed. In more details,

- concerning the **Type of study**: i) the following sentence has been introduced in the paragraph "3.2.1 - Type of LCA study" to explain why aLCA is more applied respect to cLCA: "*aLCA is by far most applied respect to cLCA mainly because it is usually focused on the identification of the environmental impact of few AD plants and it required a less comprehensive inventory in particular with regard to the marginal technologies affected by the AD plants.*";
- concerning the **Functional unit**, the following sentences have been introduced in paragraph "3.2.2 – FU": "*Among the 69 studies reviewed in Table 1, the adopted FU was: the produced electric energy in 23 studies, the cogenerate electricity and heat in 6, the volume of biogas or biomethane in 5, the energy in the biogas biomethane in 10, the amount of digested feedstock in 8, the main process from which the digested waste arise (e.g., milk, tomato purea, meat) in 3, mixed and site specific units (e.g., 1 year of farm operation, the volume of the digester, in the*

remaining studies. The wide variability of FU, although justified by the different aims of the reviewed LCA studies, raises serious problem for what concern the comparability among the different results."

- Concerning the system boundary and the multifunctionaly issue the following sentences have been added in the paragraph "future trends": "*When aLCA, allocation is performed among the different products and co-products. Regarding the digestate, the accounting of credits considering the replacement of mineral fertilizers production based on the digestate content in N, P and K should be avoided. First because the digestate is frequently applied on soil that, due to the application for several years of animal slurries, doesn't require fertilization with P and K and, secondarily, because the efficiency of mineral fertilizers is considerably higher respect to the one of the digestate.*".

For all the aspect above mentioned, a further discussion has been introduced in paragraph 7 "**Future trends in LCA application to agricultural AD systems**".

The term "multifunctionally issue" was included in Table 1, but I cannot see how it is related with Table 2 since it is presented in a different way. It is better to be more consistent in the terminology.

Following your suggestion Table 1 has been removed and, in the Table 2 (now Table 1), the caption related to the multifunctionality issue has been changed and it is now more explicit: "Multifunctionality issue"

Discussion

An evaluation of possible future trends in LCA study regarding all this methodological aspects would improve notoriously the quality of the paper (including an analysis of the evolution of LCA studies).

Done, following your suggestion we introduced a new paragraph 7 "**Future trends in LCA application to agricultural AD systems**".

Case studies

Figure 3 is very confusing. The differences among the plants under study are very difficult to understand in Figure 1 and the system boundaries cannot be understood. In addition, only 3 plants are included. A more graphical figure (like a flowchart) would help to understand how the plants work.

It is true figure 3 is quite complicated. Nevertheless, it is a graphical representation of the different biogas plants that, due to reasons of synthesis, cannot be described in details into the text. We think that it could be useful for the readers.

There are only three figures for the 4 biogas plants because the figure in the middle represent both the plants 1 and 3 where there is co-digestion of cereal silages and animal slurries. For clarity the figure caption has been revised and more information have been introduced. The new caption is (underlined the additional information):*"Figure 3 – System boundary for the 4 AD plants: <u>on the top plant 1 where only cereal silages are digested; in the middle, plants 2 and 3 where silages are co-digested with animal slurries; in the bottom, plant 4 fed only with animal slurries</u>. (CC: Cereal cultivation; SL = animal slurry; R: digester; T (D): digestate tank; SP: separator (LF, SF); T (LF): liquid fraction tank; S: scrubber; C: chiller; FL: biogas flare; HE: heat exchanger; CHP: engine-generator; ICE: internal combustion engine)"*

Within the inventory analysis, how were emissions from the storage of the produced digestate calculated?

We apologize for the missing information; the following sentences have been introduced in section 5.3 "inventory": "*Emission of methane and ammonia from digestate storage in open tanks have been assessed considering the values reported by Edelman et al. (2011); in more details these emissions are equal to 8.9 kg/MWh for CH_4 and 0.23 kg/MWh for NH_3*".

The following references has been introduced: Edelmann W, Schleiss K, Engeli H, Baier U. Ökobilanz der Stromgewinnung aus landwirtschaftlichem Biogas; 2011.

Human toxicity related categories are highly influenced by heavy metals. Have been these environmental impacts computed within the application of digestate into the agricultural land? If not, are the results in these impact categories reliable? Please, justify.

It is true; toxicity related impact categories are affected by heavy metals contained in the animal slurries. However, also without AD, the slurry will be spread on the fields and the same amount of heavy metal will be applied to the soil. Respect to the reference scenario, with the AD, the same amount of heavy metals reached the fields because the digestion does not affect their amount. For this reason, heavy metals have been excluded from the system boundary.

The following sentence has been added in the "system boundary section" (5.2): "*Heavy metals contained in the animal slurries have been excluded from the system boundary because their amount is not affected by the AD. The heavy metal amount applied using the digestate is the same that will be spread using directly the animal slurry as organic fertilizer*."

Editors:

- An updated and complete literature review should be conducted. The relevance to Applied Energy should be enhanced with the considerations of scope and readership of the Journal.

Dear Editor, following your suggestion we expanded the literature review. In more details, the following references have been added:

Edelmann W, Schleiss K, Engeli H, Baier U. Ökobilanz der Stromgewinnung aus landwirtschaftlichem Biogas; 2011.

Murto, M., Björnsson, L., Mattiasson, B. (2004). Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure. *Journal of environmental management*, 70(2), 101-107.

Sadhukhan, J. (2014). Distributed and micro-generation from biogas and agricultural application of sewage sludge: Comparative environmental performance analysis using life cycle approaches. *Applied Energy*, 122, 196-206.

Show, K. Y., Lee, D. J., & Tay, J. H. (2012). Anaerobic Digestion of Sewage Sludge. Biological Sludge Minimization and Biomaterials/Bioenergy Recovery Technologies, 319-347.

Sosnowski, P., Wieczorek, A., & Ledakowicz, S. (2003). Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. *Advances in Environmental Research*, 7(3), 609-616.

Zhang, W., Wei, Q., Wu, S., Qi, D., Li, W., Zuo, Z., Dong, R. (2014). Batch anaerobic co-digestion of pig manure with dewatered sewage sludge under mesophilic conditions. *Applied Energy*, 128, 175-183.

Messagie, M., Mertens, J., Oliveira, L., Rangaraju, S., Sanfelix, J., Coosemans, T., Van Mierlo, J., Macharis, C. (2014). The hourly life cycle carbon footprint of electricity generation in Belgium, bringing a temporal resolution in life cycle assessment. *Applied Energy*, 134, 469-476.

Jin, Y., Chen, T., Chen, X., Yu, Z. (2015). Life-cycle assessment of energy consumption and environmental impact of an integrated food waste-based biogas plant. *Applied Energy*, 151, 227-236.

Zheng, Z., Liu, J., Yuan, X., Wang, X., Zhu, W., Yang, F., Cui, Z. (2015). Effect of dairy manure to switchgrass co-digestion ratio on methane production and the bacterial community in batch anaerobic digestion. *Applied Energy*, 151, 249-257.

- Review Articles:
APEN invites subject reviews from accomplished researchers and scholars in a broad range of topics within the scope of the journal. Reviews are to be in-depth, critical analyses. Review authors are those who have the demonstrated track record and can write with authority on the proposed topic. Reviews may be undertaken on a broad subject area or on a very specific topic, and are expected to be more than just a survey of the literature accompanied by a long list of references. APEN welcomes reviews that present the state-of-the-art and the critical issues that have been solved and those challenges that remain unresolved. We particularly appreciate reviews that provide insights about where the current research is heading and those issues that attract significant research and development in the near and far future. The results should be further elaborated to show how they could be used for the real applications.

We introduced the new paragraph 6 "**Future trends in LCA application to agricultural AD systems**" to discuss the future trends of LCA application to agricultural AD plants.

In the follow the new paragraph:

6. Future trends in LCA application to agricultural AD systems

Over the years, the application of LCA to agricultural biogas plants allowed to depict the environmental impact related to this renewable energy source as well as to highlight the mitigation strategies that can be undertaken to improve AD sustainability [132]. Nevertheless, there are unsolved challenges and methodological choices that should be harmonized for improving the robustness of LCA results and to make the outcomes of different studies comparable.

6.1 Challenges

As highlighted in the presented case studies and in several previously carried out researches (see Table 1), feedstock production and emissions from digestate storage are the main responsible for the environmental impacts for most of the commonly evaluated impact categories. Therefore, concerning feedstock production, primary data should be collected also considering the wide geographic and temporal variability of cultivation practices and biomass yield. For this aspect, the use of secondary data affects the reliability of *the results. With regard to digestate emissions, primary data collection is expensive, hazardous and time-consuming; consequently, the use of secondary data is frequently inevitable. Nevertheless, site-specific data should be used to assess these emissions, as they are deeply affected by climatic conditions.*

6.2 Methodological issue

For what concern the LCA type, although nowadays aLCA is the most applied, in the future, the cLCA will be probably more widespread in the future. The environmental aspects related to agricultural AD plants will be evaluated more and more considering not only their absolute impact (evaluable with an aLCA) but also their effect on the local production systems and, in particular, on the marginal technologies that biogas plants could displace/affect. Whith aLCA, allocation is performed among the different products and co-products. Regarding the digestate, the accounting of credits evaluated considering the replacement of mineral fertilizers production based onthe digestate content in N, P and K should be avoided. First, because the digestate is frequently applied on soils that, due to the application of animal slurries for several years, do not require fertilization with P and K and, secondarily, because the efficiency of mineral fertilizers is considerably higher respect to the one of digestate.

When the outcomes of LCA studies have to be compared with results of other researches, the selected FU should be:

- *for plants fed also with energy crops: the produced electricity if biogas is used into an ICE CHP or the volume of produced methane in case of plants where biogas is upgraded to biomethane;*
- *for plants fed only with waste (e.g., animal slurry): the mass of digested feedstock.*

Finally, the choice of the LCIA method should be carefully evaluated considering the goal of the study and, in particular, the assessed impact categories. When the study aims to assess AD plants fed by energy crops, a LCIA method able to properly quantify the impact categories affected by fertilizer related emissions (e.g., acidification and eutrophication) should be selected. If the study compares biogas plants of different size, to highlight the plants differences in term of building and maintenance, LCIA methods such as Recipe, CML and ILCD should be adopted."

***Highlights (for review)**

- A comprehensive review of LCA studies focused on agricultural AD plants was done
- Goal and scope, impact assessment method, feedstocks and location vary widely
- Four agricultural AD plants in Italy are also considered in in this study
- Energy crops and digestate emissions are the main contributors to the impact
- Covering the digestate storage and exploit the surplus heat are effective solutions

Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable

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Field Code Changed

Abstract

Anaerobic Digestion (AD) has been recognized as a~~n~~ ~~effective~~ viable solution to ~~reduce greenhouses gases (GHG) and to~~ produce renewable energy and to reduce global warming especially when secondary feedstock and/or wastes are used. Several LCA studies analysed the environmental performances of biogas production systems. The results of this review highlight that the goal, scope, life cycle impact assessment (LCIA) methodology, feedstocks and geographical regions covered by the studies vary widely. Most studies are based in Europe, several in China and few in South and North America and in Africa.

To better highlight how the choices on the feeding mix~~ture~~, the digestate storage, the surplus heat valorisation as well as the plant size can affect the environmental performances of agricultural AD plants ~~Four~~ four ~~agricultural AD~~ plants ~~we~~in ~~Italy are also considered~~ have been analyzed in in this study. The results suggest that the ~~cereal silage~~ energy crops production and the operation of anaerobic digesters, including digestate emission from open tanks, are the main contributors to the impacts from biogas electricity. This entails that it is environmentally better to have smaller plants using slurry and waste rather than bigger plants fed with energy crops. Recovering heat waste as well as covering of digestate tank would improve significantly the environmental sustainability of biogas electricity, and particularly the global warming category.

Keywords

Renewable energy, environmental impact, life cycle assessment, mitigation strategies, biogas, comprehensive review.

1. Introduction

Anaerobic Digestion (AD) has been recognized as an effective solution to reduce greenhouses gases (GHG) and to produce renewable energy especially when secondary feedstock and/or wastes are digested [1-3] ~~(Messagie et al., 2014; Jin et al., 2015; Pierie et al., 2016)~~. In fact, AD plants can be fed with a wide range of feedstock. The AD of the organic fraction of municipal solid waste (OFMSW) [4-6] ~~(Patterson et al., 2011; Righi et al 2013; Evangelisti et al., 2014)~~, sewage sludge [7-10] ~~(Sosnowski et al., 2003; Murto et al., 2004; Show et al., 2012; Zhang et al., 2014)~~ and food waste [11-13] ~~(Bernstad and Cour Jansen, 2012; Laurent et al., 2014; Sadhukhan, 2014)~~ is by far one of the most rational solutions to manage this waste, this matrix is of the most used feedstock for biogas production: nevertheless, for what concern the agricultural and agro-industry sectors the suitable feedstock are several. Besides energy crops (e.g., cereals, grass, mischantus, switchgrass and sunflower) specifically cultivated, animal slurry and manure as well as waste (e.g., pomace, vegetable residues, tomato peel and skin, slaughterhouse waste) and by-products (from winery and distilleries, from biodiesel production, from cereal mill) of the main agro-industries can be digested [14-16] ~~(Zheng et al., 2015 ; Hijazi et al., 2016; Fusi et al., 2016)~~.

In this context, in the last years, thanks also to favourable public subsidy framework, several agricultural AD plants have been built in particular in Europe [15] ~~(Hijazi et al., 2016)~~. This rapid expansion in Europe is largely due to the feed-in-tariffs (FiT) schemes available in 29 countries [17] ~~(Whiting and Azapagic, 2014)~~. For example, in Italy, the electricity produced by AD plants smaller than 1 MW and built before the 2013 is paid 280 € per MWh [18-19] ~~(Negri et al., 2016)~~. In the UK, the subsidies are significantly lower, ranging from 130-210 €/MWh, depending on the plant size ~~(Whiting and Azapagic, 2014)~~[17].

Production of biogas is expanding rapidly in Europe. According to EurObserv'ER [20] ~~(2015)~~, about 14.9 million tonnes oil equivalent (Mtoe) of biogas primary energy was produced in the EU during 2014, which equates to 6.6% growth on the previous year. However, despite this grow, the same sector trend of slower growth than in previous years, because of the biogas policy U-turns made by the European Union's two major producer countries, Germany and Italy. Germany, with 8726 AD plants, 3905 MW of installed capacity and 29 TWh of electricity produced, is the largest producer of biogas, not only in Europe but in the world [20] ~~(EurObserv'ER, 2015)~~. Italy follows at 8.2 TWh of electricity produced by 1700 AD plants in 2014 (+10% respect to 2013) with the total installed capacity of about 1000 MW [18, 20] ~~(EurObserv'ER, 2015; Negri et al., 2014b)~~. In Austria, about 400 agricultural AD plants are currently running with an installed electric capacity of 107 MW [21]. ~~(Kral et al, 2016)~~

In order to assess the environmental impacts that are associated with producing and utilizing biogas as an energy carrier, the method of Life Cycle Assessment (LCA) can be applied [22-23] (ISO, 2006). Several LCA studies in Europe and worldwide focused on environmental assessment of biogas production systems. This should provide a solid knowledge base for both policymakers and engineers to improve the efficiency of such systems and reduce their environmental impacts. At the same time, comparing different LCA studies can be challenging due to differences in scope and a lack of documentation. Fusi et al. ~~(20~~[16~~)~~] analyzed 26 different studies focused on AD plants and found that only five have considered a full suite of impacts normally included in LCA evaluation; among these studies the goal, scope, life cycle impact assessment (LCIA) methodology, feedstocks and geographical regions covered by the studies vary widely making difficult the comparison of the results. Hijazi et al [15] carried out a review focused on agricultural biogas plants in Europe ~~-~~and ~~focusing the attention only on the European context and~~ considered~~ in~~ a ~~really~~ small number of LCA studies (only 15). There is a lack of a comprehensive review with a comparison of all the LCA studies focused on agricultural AD plants around of the world considering both methodological and operational aspects.

The aim of this study is twofold: first, to perform a review of the LCA studies carried out in the different countries focusing on agricultural AD plants and second, to present the results of selected case studies in order to highlight how the environmental results are affected by methodological choices as well as by operational aspects.

~~The manuscript is organized as follows. In sections 2-4 the review analysis is described and the main results are reported and discussed, while in section 5, some case studies are analyzed.~~

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2. Materials and methods

The goals of this review are:

- Summarize the current knowledge of the methodology of LCA studies of agricultural biogas systems,
- Systematically compare different LCA-studies of agricultural biogas systems to get a rigorous review,
- Make a synthesis of the achieved results and conclude on the status of environmental impacts associated with agricultural biogas ~~production~~ plants ~~in Europe~~ worldwide in order to identify measures for its reduction~~ing GHG and other emissions from biogas systems~~.

~~For this re~~To this ~~view~~aims~~, 105~~ scientific manuscripts were selected in Web of Science™ databases by combing the following keywords “Life Cycle Assessment”, “LCA”, “anaerobic digestion”, “biogas”, “carbon footprint” and “GHG emissions”.

Among the 105 studies identified, 68 were reviewed in detail~~These studies were selected~~ according to the following criteria:

- ~~The~~ To ~~analysis~~ analyse ~~of~~ the environmental performance of the AD process carried out in agricultural biogas plants ~~must be~~is the main aim of the study;
- The feeding of the AD plants should involves at least one of the following feedstock: energy crops, animal waste, other agricultural by-products and waste from agro-industry; therefore, studies dealing only on municipal solid waste AD for biogas production were not considered;
- To reflect the actual state of the art and recent developments as well as the application of updated LCA method only studies published in the last 15 years were included;
- Only studies published in peer-review scientific journals were considered, conference papers, Ph.D. and Master Theses were not taken into account;
- The study must include at least the impact category Global Warming Potential (GWP);
- Studies must be based on defined methods such as LCA [22-23] (ISO 14040 and 14044), carbon footprint [24] (ISO, 2013) or EU Renewable Energy Directive RED [25] ~~(European Commission, 2009)~~ or the applied methodology must be fully explained.

~~Among the 105 studies previously identified, 68 were reviewed in detail and the methodological and operational aspects reported in **Table 1** were identified.~~

~~**Table 1** - around here~~

3. Review results

The main review results are reported in **Table ~~2~~1**. Among the 69 analysed studies, 56 referred to agricultural AD plants built in Europe, 6 in Asia, 4 in North-Centre America, 2 in South America and only 1 in Africa.

Table ~~2~~ 1 - around here.

3.~~2~~1 Operational aspects

3.~~2~~1.1 Number of AD plants analysed and their size

Although in most of the studies (34) only one AD plant was analysed, in others more than one agricultural biogas plants were evaluated, differentiated for feeding, size and technological aspects. The plants have a capacity below 1 MW, with the majority being around 500 kW and only few below 100 kW.

3.2.2 Feedstock

A wide variety of feedstock was used to feed the plants; (see **Table S1 in Supplementary Materials** for more details) 4 typologies can be identified:

- Energy crops, crops specifically cultivated for biogas production. Among these, the cereals were by far the most used. However, in particular in Countries where public subsidies are granted for electricity and/or biomethane production by biogas (e.g., Germany, Italy and UK), the agricultural AD plants are fed mainly with cereal silages. Although also considerable amount of animal effluents (slurry and manure) are digested, the main fraction of produced biogas arises from cereal silages. Among these, the maize was the most used thanks to its high specific biogas production [98] ~~(Bacenetti et al., 2015b)~~, storability and biomass yield [99] ~~(Negri et al., 2014a)~~: in 38 of the 69 analysed LCA studies maize silage was digested. This kind of feedstock is usually fed into AD plants characterized by medium-large size (electric power >300 kW) in co-digestion with other feedstock characterised by high moisture content (e.g., animal slurry, whey). Besides cereals, also miscanthus, sugar beet, hemp, clover and sunflower were tested. In particular, Blengini et al ~~(2011)~~ [32] identify the miscanthus as the most sustainable if only GWP is evaluated.

  ;

- Animal slurry and manure from pig and cattle were the most commonly digested due to the diffusion of this kind of livestock activities; nevertheless, also poultry manure was used. As opposed to energy crops, this kind of feedstock was mainly used in small AD plants where mono-digestion is performed. Several studies highlighted how AD plants fed with animal slurry and manure achieve better environmental performance compared to the ones fed with the energy crops. This is possible because, being the slurries and manure a waste of other activities, no environmental load is associated with them; moreover their digestion was frequently associated with credits for the avoided emissions of their traditional management in open tanks [29, 58, 59, 60, 64,100] ~~(Bachmaier et al., 2010; Bacenetti et al., 2013; Lansche and Muller, 2011; Lansche~~

~~and Muller, 2012; Meyer-Aurich et al., 2012; Lijò et al., 2014a)~~. Nevertheless, the environmental performance of AD plants fed with animal effluents (above all the liquid ones, such as pig slurry) strongly depends on the transport distances, that should be minimized [29, 101, 102] ~~(Poeschl et al., 2010; Bacenetti et al., 2013)~~.

- Agricultural and agro-industry by-products and wastes, this group includes feedstock characterized by great variability in terms of dry matter content, specific biogas production, origins, availability and seasonability. Both agricultural and agro-food industry by-products and wastes are available in specific seasons of the year (usually after the harvesting) but, differently from the agricultural ones, available in small amounts in several points of the territory (e.g., straw), the agro-industrial ones are concentrated close to the processing plants (e.g., winery wastes). The spreading of feedstock on the territory, besides logistics issues, involves also high environmental impacts related to the transport distances.

The most frequently digested agricultural by-products and waste were straw (usually after specific pre-treatment), tops and leaves of sugar beets, while the agro-food ones are distiller's waste, rapeseed cake, cheese whey, milk fodder, bakery residues, winery waste, sugar beet pulp, tomato seeds and peels, fruit residues, fatty residues, oil seed residues and potatoes residues. In some studies only generic information are reported about the digested feedstock (e.g., agro-industrial wastes or biodegradable matrixes) [39] ~~(Chevalier and Meunier, 2005)~~.

3.~~1~~ 2 Methodological aspects

3.~~1~~2.1 Type of LCA study

Depending on the goal of the study two types of LCA can be performed: attributional LCA (aLCA) and consequential LCA (cLCA). aLCA describes the relevant physical input and output flows entering and exiting from a product system, whereas cLCA defines how these flows might be modified in response to a decision or a change ~~(Finnveden et al., 2009; Marvuglia et al., 2013; Styles et al., 2016)~~ [82, 103, 104]. aLCA is useful for identifying systems with important impacts, whereas cLCA is useful for evaluating the consequences of individual decisions ~~(Van Stappen et al., 2016)~~ [84]. The consequential life cycle assessment (cLCA) is a “prospective” method ~~(Rehl et al., 2012)~~ [75], it is used to identify the marginal technology substituted new technology under evaluation. In contrast to the attributional approach, where average (not marginal) technologies are used, the cLCA approach is applied to obtain information about the environmental impact changes related by a change in demand or in the output of the functional unit ~~(Rehl et al., 2012)~~ [75].

In the cLCA approach "system expansion" and "substitution", also called "system enlargement" or "crediting" is used to solve multi-functionality (processes with more than one output product) [103] ~~(Marvuglia et al., 2013)~~. On the contrary, in aLCA allocation is used to solve multi-functionality (see. Section 3.1.5).

In many LCA studies about energy generation from AD plants, there was no differentiation between aLCA and cLCA and frequently allocation and system expansion were mixed ~~(Rehl et al., 2012)~~ [75]. According to Reinhard and Zah ~~(2009)~~ [105], in cLCA the environmental results depend on the environmental scores of the marginal technology replaced rather than on local production factors. In other words, the marginal technology assumed to be affected by AD plants is the most important factor in the results.

The review results confirmed the findings of Rehl et al., ~~(2012)~~ [75] and Reinhard and Zah ~~(2009)~~ [105]: cLCA was less carried out respect to aLCA (only 10 studies out of the 69 analysed) and the majority of the studies performed aLCA but mix allocation and system expansion were used to solve the multifuntionaly issue. aLCA is by far most applied respect to cLCA mainly because it is usually focused on the identification of the environmental impact of few AD plants and it requires~~d~~ a less comprehensive inventory in particular with regard to the marginal technologies affected by the AD plants.

3.~~1~~2.2 Functional unit (FU)

ISO 14044 ~~(ISO, 2006)~~ recommends that ''the functional unit shall be consistent with the goal and scope of the study''. However, the objectives of biogas LCA studies and the functions provided by biogas systems are diversified and therefore functional units are numerous. According to their main function, the agricultural AD plants analysed in the reviewed studies can be divided into:

- plants designed with the purpose to produce energy or energy carriers (e.g., biomethane) for their subsequent selling. For these AD plants the most used FU are: (i) the delivered energy, usually electricity but also thermal energy or a mix of both, (ii) the produced volume of biogas or biomethane, (iii) the energy content in the energy carriers.

- plants built for treatment of waste (e.g., animal effluents, agro-industrial residues) in which the production of energy is only a secondary aim because the main function of the system is the improvement of the traditional management of these wastes. In this case, the FU is usually related to the amount of waste treated (e.g., 1 ton of slurry) or to the main product generated from the production system from which the waste arises. Gutierrez et al. [50] ~~(2016)~~ assessed the environmental effect of the AD of animal slurry for 1 pig of 120 kg in Cuba; Bacenetti et al [30, 31] ~~(2015a; 2016)~~ for the digestion of tomato puree by-products (peels and seeds) and cow slurry, expressed the results for 1 kg of tomato puree and for 1 kg of milk, respectively.

Some LCAs used case-specific, energy output-related functional units, such as the annual electricity and heat consumption of a village of 150 households ~~(Kimming et al, 2011)~~[57].

~~Among the~~In the 69 studies reviewed in Table 1, the ~~adopted~~ following -FU was adopted: the produced electric energy (~~in~~ 23 studies), the cogenerate electricity and heat ~~in~~ (6 studies), the volume of biogas or biomethane ~~in~~ (5 studies), the energy contained in the ~~biogas~~ biomethane ~~in~~ (10 studies), the amount of digested feedstock (~~in~~ 8 studies), the main process from which the digested waste arise (e.g., milk, tomato purea, meat) ~~in~~ (3 studies), mixed and site specific units (e.g., 1 year of farm operation, the volume of the digester, in the remaining studies). The wide variability of FU, although justified by the different aims of the reviewed LCA studies, ~~raises serious problem for what concern~~ makes the ~~comparability~~comparison among the ~~different~~ results of the different studies not always possible~~.~~.

3.~~1~~2.3 System boundary

Among the LCA studies reviewed, the system boundary (SB) varies mainly according to the feedstock used to feed the digester and to the selected functional unit. When energy crops are digested, the SB encompass also the crop cultivation while when only animal waste and/or by-products from agro-industry are used the SB focuses only on anaerobic digestion and biogas treatment/use. For LCA studies focused only on the biomethane production ~~(Adelt et al., 2011; Buratti et al., 2013; Manninnen et la., 2013; Morero et al., 2015a; Adams et al., 2015)~~ [26, 26, 63, 66, 74, 106, 107] a “gate to gate approach” was used, in particular if different upgrading technologies were compared ~~(Morero et al., 2015a; Morero et al., 2015b; Ravina et Genon, 2015)~~.

Both for energy and biomethane production, the distribution stage was usually excluded from the system boundaries.

Several capital goods are employed over the AD production process; tractors and equipment are needed for crop cultivation and/or feedstock transport, building such as silos or tanks can be used for biomass storage while, at the AD plant, digesters, tanks as well as devices for biogas treatment upgrading and utilization are always present. Manufacturing, maintenance and disposal of these goods is associated with an environmental load.

Regarding the inclusion in the system boundary of capital goods three different approach can be highlighted: (i) exclusion of capital good both at field level (energy crops cultivation) and at AD plant level; (ii) exclusion only of capital goods at AD plant level; (iii) inclusion of these goods at the two levels. Usually when energy crops were used to feed the digesters, capital goods for field operations and biomass transport were considered while the ones at AD plant level were excluded. The exclusion is supported by the low impact related to capital goods for some impact categories. For example, according to Rapport et al ~~(2011)~~ [108] and Hartman ~~(2006)~~ [109], GHG emissions related to infrastructures represent less the 4% of global emission through the whole process while, according to Bühle et al. ~~(2011; 2012)~~ [110, 111], the supply of infrastructure such as buildings, machinery, and roads contribute less than 10% to the total energy input over a time span of 20 years.

The exclusion of capital goods from the system boundary was the most frequently choice; only 19 of the 69 reviewed studies included the capital goods both at the field and the AD plant level.

Land Use Change (LUC) was taken into account in only 7 studies; usually LUC was not accounted considering that the area where energy crops is cultivated were already previously grown with this kind of crops. The LUC (direct – dLUC and indirect – ILUC), when taken into account, strongly affects the GWP impact category [82] ~~(Styles et al., 2016)~~. Hamelin et al. ~~(2014)~~ [52], who compared six different feedstock, highlighted that the maize scenario is the only one giving rise to a net global warming impact. This result was mostly due to the LUC. Unfortunately, depending on the assumptions made, the value considered for LUC widely varies. For example, in Hamelin et al. ~~(2014)~~ [52], the value considered (equal to 18 t CO_2 eq.· ha^{-1} displaced·y^{-1}) appears in the middle-high range. Lund et al. ~~(2010)~~ [112] reported a range of 10-

28 t CO_2 eq.·ha^{-1} displaced·y^{-1}, while Meyer-Aurich et al, ~~(2012)~~ [64] considered a figures of 2.6-10 t CO_2 eq.·ha^{-1}·y^{-1} (for turning hectares of German grassland to cropland production).

3.1.4 Inventory analysis and data sources

Surprisingly, concerning the foreground data[1], more than half of the reviewed studies (38) are carried out using mainly secondary data coming from literature and databases (above all ECOINVENT®). Only 14 were completely based on primary foreground data and ~~refered~~referred to literature and databases only for background data.

~~and they relate tothe~~

Primary data are usually collected via questionnaires and interviews to:

1) The farmers, who provide information on feedstock production; and
2) AD managers and operators, for data on energy production and consumption and daily feedstock requirements.

Secondary data were usually used for the assessment of emissions related to digestate application and biogas combustion in the CHP engine as well as for the evaluation of the credits arising from digestate use as organic fertilizer and from avoided traditional slurry management.

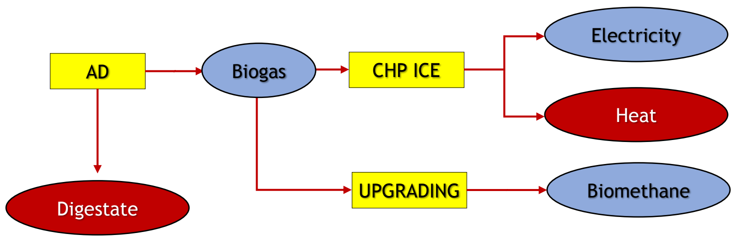
3.1.5 Multifunctionality issue

The biogas, generated together with the digestate during the feedstock digestion, can be upgraded to biomethane or be fed in a CHP ICE to produce electricity and heat (**Figure 1**). The sharing of the environmental impact among the different products, co-products and byproduct is a methodological issue that can be faced by means of allocation as well as by the system expansion ~~(Rehl et al., 2012)~~ [75].

Figure 1 around here

~~**Figure 1** - Product (in blue) and co-products (in red) achievable~~ stemming ~~from an agricultural AD plants~~

[1] Foreground data refer to foreground system i.e. core processes of the analysed production system in which actions can be directly taken and where direct measurements can often be carried out (primary data). Foreground data are distinguished from background system where usually no modification and no data measurement are possible.



In the allocation approach, the environmental burden is divided among the main product, coproducts and by-products using physical properties such as mass, energy, exergy or economic value ratios. According to ISO standards ~~(ISO, 2006)~~ [22, 23], allocation should be avoided by means of system expansion. In the reviewed LCA studies, the system expansion approach was usually carried out for the digestate. To solve the multi-functionality related to the cogenerated heat, two main trends were found in the reviewed studies: (i) when the heat is wasted, all the environmental impact is ascribed to the electricity, (ii) when the heat is recovered ~~instead~~, the "system expansion" and the allocation based on exergy content were the usually used approaches. In Rana et. al. ~~(2016)~~ [73] and Manninen et al. ~~(2013)~~ [63], consistently with the RED methodology, the co-products allocation procedure was performed using an energy-content based criterion to account for the digestate fractions not reused within the system and modelled as co-products. The allocation procedure was based upon the Lower Heating Value~~s~~ (LHV) values related to biogas, and both Solid Fraction and Liquid Fraction of the digestate.

According Manninen et al. ~~(2013)~~ [63], it is questionable whether the RED calculation rules are suitable for a multifunctional production system such as biogas production system. Indeed if the co-product generated (e.g. digestate) has an energy content of zero, and it is not used for energy production, energy allocation is not the best method to use ~~(Manninen et al., 2013)~~.

Concerning the accounting of environmental benefits arising from the use of digestate as fertilizer, different approaches were identified. Some studies ~~(e.g., Dresseler at al. 2012; Bacenetti et al., 2013; Fusi et al 2016)~~ [16, 29, 45] consider that the digestate is used to fertilize the energy crops in a close loop where only indirect environmental benefits (derived by the reduction of chemical fertilizers needing) are accounted. However, in the majority of the studies, a substitution approach was considered: the digestate, depending on its nutrient content, is supposed to avoid the production of mineral fertilizers and, therefore, the environmental impact of chemical fertilizers production. The latter is credited to the

AD process. For the N, P and K in the digestate, different mineral fertilizer equivalents (MFE[2]) were considered. Usually for P and K the MFE is equal to 100% while it is lower for N depending on its NH_4 component ~~(Wulf et al., 2006)~~ [87]. Only few studies accounted the credit for digestate considering the real needing of the soil; for example Hamelin et al. ~~(2011)~~ [53] account a MFE equal to 0% for P and K in Danish soils where, due to slurries application for several years, the level of phosphorous and potassium is adequate for cereal cultivation even without digestate application.

Due to P accumulation in the soil ~~(Hansen et al., 2006b)~~ [113], the accounting of the digestate credits for the replacement of P fertilizers should be avoided, in particular for soil fertilized with animal slurry and manure for several years.

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3.1.6 LCIA methods and evaluated impact category

The greatest variation among the studies was found in the number of impacts considered and the methodologies used to estimate them. The former range from one to 18 and the latter cover almost all known LCIA methods, including the EcoIndicator 99, CML 2001, Impact 2002+, ReCiPe and ILCD methods. The Global Warming Potential (also called Carbon Footprint or Climate Change impact category) is the only impact evaluated in all the reviewed studies, however also for this impact category different methods were used for the assessment: IPCC 2007 ~~(IPCC, 2007)~~ [114], RED ~~(European Commission, 2009)~~ as well as the standard ISO/TS 14067:2013 ~~(ISO, 2013)~~ [24].

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4. Discussion

4.1 Main results

For what concern the global warming potential, the agricultural AD plants evaluated in the different reviewed studies usually achieved better environmental performances compared to the reference systems based on fossil fuels (e.g., natural gas, electricity from coal or natural gas, etc.). For the studies in which the electricity is selected as functional unit, the Global Warming Potential (GWP) results, reported in **Figure 2** showed a huge variability. In particular, the highest value (0.55 kg CO_2eq/kWh) was recorded by Siegl et al. ~~(2011a, 2011b)~~ [79, 80] for small AD plants (50-150 kW) fed with cereal silage in Austria while the lowest GWP (-1.72 kg CO_2eq/kWh) was reported by Boulamanti et al. ~~(2013)~~ [35] for plants fed by

[2] MFE, measure of the efficiency of the nutrient in the digestate to substitute an equal amount of nutrient from mineral fertilizer.

manure with covered digester storage tanks. Although, this variability was mainly due to the assumptions made (e.g., methane losses for leakages, emissions from digestate, allocation) and to the system boundary (e.g., avoided emission from traditional manure management, avoided emission from the composting of agricultural residues and other wastes) some general conclusions can be drawn:

- Respect to electricity from fossil fuel, the electric energy produced in the agricultural AD plants showed, also in the worst cases ~~(Siegl et al., 2011; Rehl et al., 2012 and Boulamanti et al., 2013)~~ [35, 75, 79, 80], lower GWP;
- GHG emission savings (negative values for GWP) were achievable only if credits for mineral fertilizer substitution and/or heat and avoided traditional manure management were considered;
- AD plants fed mainly with animal slurry and agricultural and/or agro-industry by-products and waste performed better than the ones fed with cereal silages;
- covering the tanks for digestate storage and exploiting the surplus heat are the most feasible solutions to improve the GWP of agricultural AD plants ~~(Rehl et al., 2012; Bacenetti and Fiala, 2015; Fusi et al., 2016)~~ [16, 28, 75].

~~**Figure 2** - Comparison among of the GWP results for electricity production among the different LCA studies (the bars represent the minimum and maximum value achieved while the dot the single value)~~

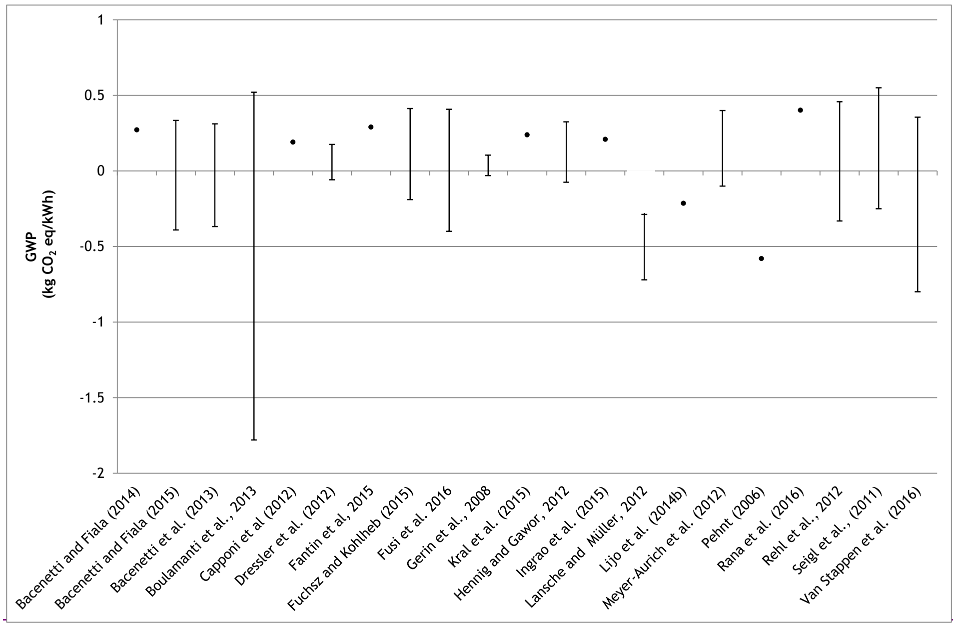


Figure 2 around here

Surplus heat valorisation deeply affects the environmental performances of electricity production form AD plants. In the study carried out by Ravina and Genon. ~~(2015)~~ [74], the direct combustion of biogas in ICE CHP unit was the most favourable solution in terms of GWP only if surplus heat is used. For plants fed only with cereal silage, sustainability was strongly reduced (and in some cases can come less) if the cogenerated thermal energy is not fully exploited ~~(Patterson et al., 2011; Poeschl et al., 2010; Poeschl et al., 2012b; Ravina and Genon, 2015)~~ [4, 71, 74, 101, 102].

Chevalier and Meunier ~~(2005)~~ [39] demonstrated that biogas co- or tri-generation was always environmentally friendly with respect to global warming and resources depletion as long as the distance for collecting crops from farms is not too far (20-50 km). Tri-generation, also referred to as CHCP (combined heating, cooling and power) allows greater operational flexibility extending the use of co-generation when there is no need for heat.

Concerning the other impact categories and, in particular, eutrophication and acidification, the main differences were found between the AD plants fed with energy crops and the ones fed with feedstock other than energy crops. When energy crops were used, the electricity from biogas scores higher in the eutrophcation and acidification categories than the electricity from fossil fuels ~~(Dressler et al., 2012; Poeschl et al., 2012a; Bacenetti et al., 2013; Fusi et al. 2016)~~ [16, 45, 29, 101]. This was mainly due to the use of fertilizers (and to their related emissions such as N and P compounds into air, soil and water) during crop growing.

Regarding the biomethane production, the comparison among the different studies is difficult due to the selection of different functional units. According to several studies, biomethane production represents a viable alternative to fossil fuels, in particular for transports. In particular, a GHG saving when biomethane is used for transports was reported by Poeschl et al. ~~(2010)~~ [71, 101, 102] (1.15 kgCO_2eq/kg biomethane) and by Power and Murphy ~~(2009)~~ [115] (between 0.017 kg/MJ and 0.02 kg/MJ depending on the feedstock). The GHG performance of the different crop-based biomethane systems was calculated by Börjesson et al. ~~(2015)~~ [33]: the results range from 22 to 47 kgCO_2eq/GJ biomethane when credit of increased soil organic carbon (SOC) content was excluded, and from −2 to 45 kgCO_2eq/GJ biomethane when it was included. Berglund and Borjesson ~~(2007)~~ [34] included in the calculation of life cycle emissions of GHGs the changes in soil organic carbon (SOC) content. Changes in SOC due to crop residues and digestate added to the soil were accounted for using the Introductory Soil Carbon Balance Model (ICBM). In this study, ley crop-based biogas systems led to a “negative” net contribution of GHG emissions due to the significant SOC accumulation in these cultivation systems.

4.2 Contribution analysis

The contribution analysis, aimed at identifying the environmental hotspots of the system investigated, was not performed in all the reviewed studies.

Feedstock production and transport represented the main contributors to the environmental impact in particular when energy crops were used or when by-products and waste were transported over long distances. Energy crops were recognized as one of the main environmental hotspots in particular for impact categories associated with N and P emissions into air, soil and water. When only energy crops were fed into the digesters ~~(Dressler et al., 2012; Bacenetti et al., 2013; Lijò et al., 2014a; Lijò et al., 2014b; Lijò et al., 2015; Fusi et al., 2016)~~ [17, 45, 29, 60-62] and the biogas was fed into a CHP internal combustion engine (ICE), the environmental impact of the cogengerated electricity was close to the one of electricity from fossil fuel for what concern GWP and it is higher for eutrophication and acidification.

Methane leakages from digesters and devices for biogas treatment as well as un-combusted CH_4 in the exhaust gases strongly affect for GWP and, by a lower extent, ozone depletion. A minor role on the environmental impact was played by the other inputs used for the AD plants (e.g., lubricating oil for the CHP ICE, chemicals for biogas desulphurization, etc.) as well as by the electricity consumed by all the different devices (mixers, pumps, etc.).

As explained in section 3.1.2, the contribution of manufacturing, maintenance and disposal of digester and CHP it was not always included in the system boundary. This exclusion is not justified, in particular for small AD plants and for impact categories related to the consumption of metals and fossil resources are assessed. When only GWP is evaluated, the impact of capital good can be neglected for medium-large AD plants (e.g. with an electrical power of the CHP > 500 kW) ~~(Rapport et al., 2011; Bühle et al., 2011; Bühle et al., 2012)~~ [108, 110, 111, 116] but in all the other cases (e.g., small plants and several environmental impact considered) the construction materials have to be taken into account. For small plants (CHP ICE with power below 300 kW), the contribution of capital goods to the total impact is in fact higher than for larger plants. Furthermore in some studies ~~(Siegl et al., 2011)~~ [79, 80], the digesters of small plants are made of steel, which needs more resources than a fermenter made of concrete. Furthermore, small CHP engines often show a comparatively low electrical efficiency than bigger CHP (e.g., for CHP ICE of 1 MW of electrical power the electrical efficiency ranges between 40 to 41% while, for smaller plants, it is considerable lower: 33-35% with 200-300 kW of electrical power), this makes the results per kWh of electricity higher in all impact categories for smaller plants.

5. Case studies

In this section, the results of 4 case studies are reported to better highlight how the choices on the feeding mixture, the digestate storage, the surplus heat valorisation as well as the plant size can affect the environmental performances of agricultural AD plants. In more details, the environmental performances of 4 agricultural AD plants located in Italy were assessed.

5.1 AD plants description

The 4 AD plants are all located in Northern Italy. This region, thanks to intensive livestock activities together with proper pedo-climatic conditions for the production of cereal silages, is one of the most important European area for biogas production. In Piedmont, Lombardy, Veneto and Emilia-Romagna (Northern Italy) are located approximately 1000 agricultural AD plants, which represent about ¾ of the Italian agricultural biogas plants [18]~~(Negri et al., 2014a)~~.

All the 4 AD plants are fed with agricultural feedstock and produce biogas that is used, after being dehumidified with a chiller and desulphurised with a scrubber, in CHP ICE. The produced electricity is fed into the national grid while the cogenerated head is only partially used for digester heating; surplus heat is wasted. Electricity consumed for operating the plants (mixers, pumps, scrubber, chiller, etc.) is taken from the grid. In all the 4 AD plants, the digestate is stored in open tanks and it is used as organic fertilizer for energy crops or for fodder production. In AD plant B, the digestate is partially separated, using a screw separator, into liquid and solid fraction. The first is used to dilute the dry matter concentration inside the digester while the latter is used as organic fertilizer.

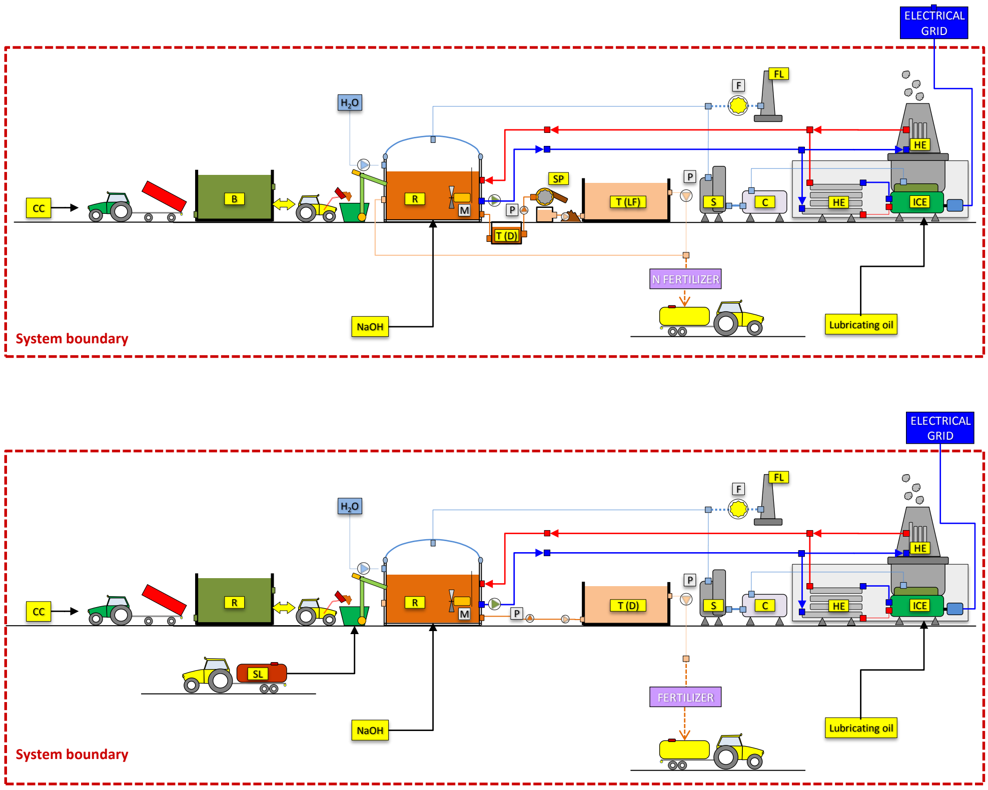
5.2 Functional unit and system boundary

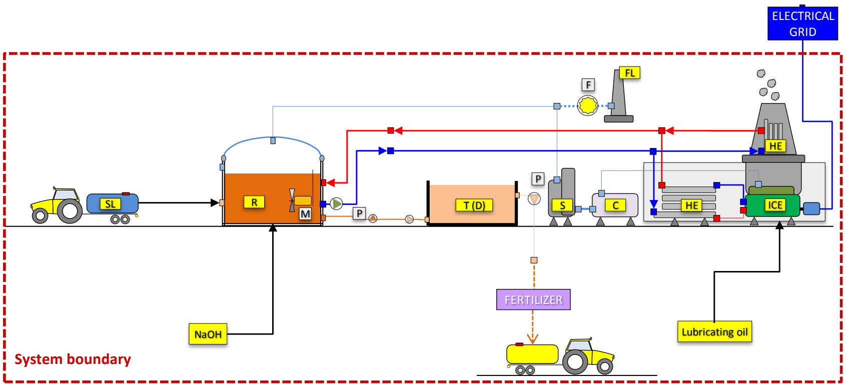
The main function of the AD plants is to produce energy and therefore the selected functional unit (FU) is 1 kWh of electricity. As clarified in section 3.1.1 the generated electricity is one of the most used FU for agricultural AD plants in particular when they are fed with energy crops.

Figure 3 summarizes the production process for the 4 different AD plants. The environmental assessment has been carried out applying a “cradle to grave” approach. Consequently, all the processes involved in the electricity production, from the extraction of raw materials needed for energy crops cultivation and AD plant construction to the disposal of waste and infrastructures, have been considered in the system boundary. No environmental impacts are considered for animal slurries as they are waste. The h~~H~~eavy metals contained in the animal slurries have been excluded from the system boundary ~~because~~ as ~~their amount is not~~they are affected by the AD treatment. The heavy metals emitted ~~amount applied~~ into the soil ~~using~~through the application of the digestate are ~~is~~ the same as if ~~that will be spread using directly t~~the animal slurry ~~as organic fertilizer~~were used.

Figure 3 - around here

~~System boundary for the 4 AD plants~~at, at ~~(CC: Cereal cultivation; SL – animal slurry; R: digester; T (D): digestate tank; SP: separator (LF, SF); T (LF): liquid fraction tank; S: scrubber; C: chiller; FL: biogas flare; HE: heat exchanger; CHP: engine-generator; ICE: internal combustion engine)~~





5.3 Inventory data

Site-specific data were directly collected by means of surveys and interviews with farmers and AD plant managers. In more details, primary specific data concerning inputs (diesel fuel, feedstock, electricity, heat, sodium hydroxide and lubricant oil) and outputs (biogas, digestate, heat and electricity) were supplied by the AD plant manager and they are referred to the year 2015.

Regarding the energy crops cultivation, primary data refers to biomass yield, transport distance and silage losses. Maize silage was cultivated considering two different cropping systems: single crop and double crop. The recorded silage yields were:

- For maize, 66.0, 68.0, 49.5 and 55.1 t/ha for plant A, B, C and D, respectively;
- For triticale 34.5, 36, 34.5 for plant A, C and D, respectively.

Additional information about inputs (digestate, fertilisers, pesticides, water and diesel fuel) and field emissions derived from fertilisers application were taken from previous studies carried out in the same area and based on primary data [29, 117-120]~~(Gonzalez- Garcia et al., 2013, Bacenetti et al., 2014, Bacenetti and Fusi, 2015, Bacenetti et. al 2016)~~. Detailed information about cereal crops cultivation is reported in **Table ~~3~~2**.

Table ~~3~~ 2 around here

Fugitive methane losses from digester and from CHP engine were considered equal to 2% in accordance with Dressler et al. ~~(2012~~[45]~~)~~.

Within the application of any type of fertilizers (organic and mineral), derived field emissions were also estimated. Nitrogen-based emissions (ammonia, nitrous oxide, nitrogen and nitrate) were calculated with factors provided by Brentrup et al. [121]~~(2000)~~. Phosphate emissions to water were estimated according to Nemecek and Kagi ~~(2007)~~[122].

Emission of methane and ammonia from digestate storage in open tanks have been assessed ~~considering~~ in accordance with the values reported by Edelmann et al. [123]; in more details these emissions are equal to 8.9 kg/MWh for CH_4 and 0.23 kg/MWh for NH_3.

Emissions associated with the avoided conventional management of animal slurry (methane, ammonia and nitrous oxide) as well as the emission from digestate were calculated with the factors provided by Amon et al. (2006) [124] for cattle slurry and Wang et al. [125] ~~, 2014~~ for pig slurry. Considering ~~that~~that, the digestate is applied as organic fertilizer during energy crops production or during the cultivation of fodder used to feed pigs and cattle no additional environmental credits were taken into account.

Combustion emissions derived from the CHP ICE were taken from NERI ~~(2010)~~[126].

Finally, background data regarding the production of all required inputs such as diesel fuel, sodium hydroxide, lubricant oil and electricity, fertilisers as well as capital goods (construction materials, their transport and landfilling) were taken from Ecoinvent® database [122, 127-130]~~(Althaus et al., 2007; Dones et al., 2007; Jungbluth et al., 2007; Spierman et al., 2007; Nemecek, T., Käggi, 2007; Hischier et al., 2009)~~.

A life span of 20 and 10 years has been considered for the digesters and for the CHP engine, respectively [16] (Fusi et al., 2016). Since the data for construction materials for the digesters and CHP engines in Ecoinvent correspond to a different plant size (800 m^3 for the digester and 160 kW of 1000 kW for the CHP engines), the environmental impacts from their manufacture have been estimated by scaling up or down to the sizes of the AD and CHP plants considered in this study. This has been carried out following the approach used for cost estimation in scaling process plants [16-17]~~(Whiting and Azapagic, 2014; Fusi et al., 2016)~~.

The main inventory data are reported in **Table ~~4~~3**.

Table ~~4~~3 - around here

5.4 Impact assessment

The environmental impacts have been ~~based~~ evaluated using the ~~on a~~ composite ~~method using~~ midpoint LCIA method recommended by the International Reference Life Cycle Data System (ILCD) Handbook [97]~~(Wolf et al., 2012)~~. The following impact categories were considered: global warming potential (GWP), ozone depletion (OD), particulate matter (PM), human toxicity (HT), Photochemical ozone formation (POF), terrestrial acidification (TA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FEx), and mineral and fossil resource depletion (MFRD).

5.5 Environmental results

Figure 4 shows the results of the environmental impact assessment for the 4 AD plants. The different inputs and outputs were gathered as follow:

- Feedstock production and transport includes the cereal silage production (when occurs) as well as silage and slurry transport;
- Infrastructures considers the construction of the AD plant (digesters and CHP engine) and its maintenance and disposal;
- CHP emissions in air by the exhaust ICE gases;
- Digestate emissions in air;
- Avoided emissions from slurry, which accounts the avoided emissions arising from traditional slurry storage in open tanks;
- Others, involves the methane losses as well as the consumption of electricity, NaOH, water and lubricating oil.

Figure 4 around here

5.5.1 Global Warming Potential

AD plants fed with cereal silages show higher GWP respect to the ones fed only with animal slurry. In more details, Plant A, where only maize and triticale silages are used, shows an emission of GHG comparable with the one of Italian electricity mix ~~(Fusi et al., 2016)~~[16]. Electricity from plants C and D, where cattle and pig slurry are fed to the digesters, involves a GHG savings (-0.37 and – 1.44 kg CO_2eq/kWh in plant C and D, respectively). From one side the digestion of animal slurry allows to produce biogas by valorising a waste without environmental burden and, from the other side, it involves considerable credits due to the substitution of the traditional slurry management (and related emissions in air - above all CH_4 and NH_3). Feedstock production and digestate emissions are the main environmental hotspot for this impact category while infrastructures and CHP emissions play a minor role.

5.5.2 Ozone depletion

Remarkable differences can be highlighted among the 4 plants; compared to plant A, plant D shows a lower impact (-44%). The main environmental hotspots are feedstock production and transport, for the plants fed with cereal silages, and methane losses. The infrastructures, responsible for a negligible impact for medium and large plants (<5%) represent about 10% of the overall impact for the small plant (Plant D).

5.5.3 Human toxicities

For both Human toxicities (Cancer effects – HTc and no cancer effects - HTnoc), bigger plants show slightly the worst performance but the differences among the ~~4~~ four biogas plants are small in particular for HTnoc. For what concern the contribution analysis:

- in HTc, feedstock production and transport and infrastructure are the hotspots; overall they contribute from 76 to 83% to the environmental load. The impact of feedstock is high for medium-large plants fed with cereal silages (from 47 to 59%) and lower for the small plant D (19%). On the contrary, the impact of infrastructures is predominant in plants fed with slurry and characterized by high specific digester volumes (36% and 56% in plant C and D, respectively) and less important in the other plants fed mainly with cereal silages (24% and 26% in plant A and B, respectively);
- in HTnoc, the key-aspects are the CHP emissions (57-60% in all the AD plants) and, again, the feedstock (31-40%).

5.5.4 Particulate matter, terrestrial acidification, eutrophications, freshwater ecotoxicity

All these impact categories show a similar trend: feedstock production and transport is by far the main hotspot when cereal silage is used. Plant D, fed only with animal slurry, has considerably better results: respect to plant A (the worst) it scores 4.3 times lower for PM, 6.3 for TA, 7.3 for TE, 65.4 for FE, 7.2 for ME and 34.7 for FEx. The role of emission from digestate, although minor respect to feedstock production and transport, cannot be neglected in PM and TE, mainly due to the ammonia emission into atmosphere.

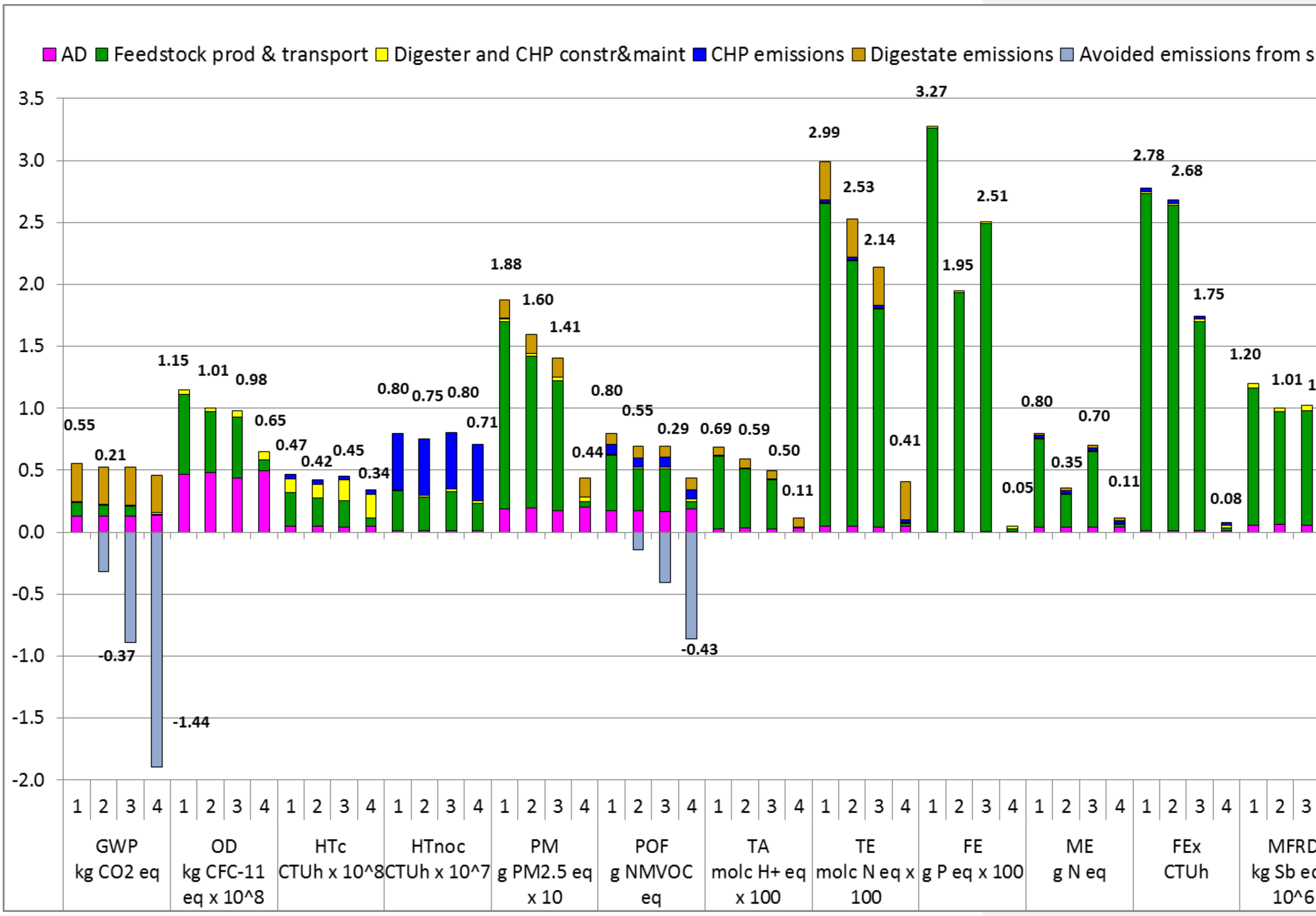
5.5.5 Photochemical oxidant formation

As for GWP also for this impact category, the digestion of slurry involves environmental credits; nevertheless, these credits allow to offset the environmental impact only for Plant D. The environmental hotspots are feedstock production and transport, methane losses and digestate emissions while the infrastructures play a minor role.

5.5.6 Mineral, fossil & renewable resource depletion

For MFRD, the result ranges from 0.49 to 1.20 mg Sb eq./kWh, AD plants fed with cereal silages have similar results while plant D performs better. Feedstock production and transport is the main hotspot (>90% for plants A, B and C and 76% in plant D); for the smaller plant (Plant 4), the infrastructures are responsible for 12% of the impact. The impact of CHP and digestate emission is negligible in all the AD plants.

~~Figure 4 - Environmental impact results for 1 kWh of produced electricity~~



5.5.6 Alternative scenarios

To test the robustness of the results as well as to evaluate how the environmental performance of electricity from biogas is affected by different technological solutions and methodological choices, different scenarios were considered:

- covered digestate storage: this scenario involves the reduction of digestate emissions by 80% according to Oenema et al. (2012)[131] as well as the construction of AD plants characterized by covered tanks. To this regard the specific process “Anaerobic digestion plant, agriculture/CH” in the Ecoinvent Database has been used instead of “Anaerobic digestion plant, agriculture covered/CH” process. The impact of covering digestate tanks is reported in **Table ~~5~~4**; the effects are negligible only for HTc, HTnoc, FE, ME and FEx while is relevant for all the other impact categories. In more details, for GWP, plant A almost halves its GHG emissions, plant B offsets its score and turns to produce benefits while plants C and D expand the magnitude of these benefits. In absolute terms, storing the digestate in covered tanks allows a GHG emission savings ranging from 0.26 kg CO_2eq/kWh in plant D to 0.27 kg CO_2eq/kWh in plant A. The mineral and fossil resource depletion (MFRD) impact increases for all the plants considered due to higher material and energy consumptions related to the building of covered digestate tank.

Table ~~5~~ 4 around here

- surplus heat valorisation: in this scenario the thermal energy not consumed for digesters heating is exploited in a district heating and it substitutes heat produced in domestic boiler from natural gas (marginal technology). Three different share of valorisation (25%, 50% and 100%) have been considered. The results are shown in **Table ~~6~~5**. When the heat is valorised environmental benefits are achieved in all the impact categories. OD is the environmental impact where the benefits are more evident (impact reduction ranging from 80-85% with 25% of surplus heat exploited to 300-330% with 100% of surplus heat exploited) but also GWP, HTc, POF and MFRD achieve considerable impact reductions. With a full valorisation of surplus heat, GWP is reduced by 10%-46%, HTc by 48-54%; POF by 33-79% and MFRD by 24-35%. The other impact categories (HTnoc, PM, TA, TE, FE, ME, FEx) are less affected by heat valorisation. These impact categories are, in fact, the ones most affected by feedstock production and by the marginal technology.

Table ~~6~~ 5 around here

- exclusion of capital goods: in this scenario the impact related to the construction and maintenance of digesters, CHP system and all the other infrastructures characterizing the AD plants (dump, pre storage tanks for slurry) has not been considered. The results for this scenario are reported in **Table ~~7~~6.** As can been inferred from the table, all plants beneficiate from the exclusion of the impact of capital goods and the best results are obtained in GWP, HTc and MFRD. The construction, maintenance and disposal of the capital goods have a higher impact on small AD plants (e.g., Plant D) while for the bigger plants slightly affect the impact categories except HTc, to which they contribute by XX% .

As highlighted in section 3.1.3, the contribute of infrastructure to small AD plants is proportionally higher because they are fed with feedstock with lower specific methane production and, consequently, the digester specific volume is bigger (19.1 m^3 of digester/kW for plant D and 11.9 m^3 of digester/kW for plant A).

Table ~~7~~ 6 around here

6. Future trends in LCA application to agricultural AD systems

Over the years, the application of LCA to agricultural biogas plants allowed to depict the environmental impact related to this renewable energy source as well as to highlight the mitigation strategies that can be undertaken to improve ~~its~~AD sustainability [132]. Nevertheless, there are unsolved challenges and methodological choices that should be harmonized for improving the robustness of LCA results and to make the outcomes of different studies comparable.

6.1 Challenges

As highlighted in the presented case studies ~~as well as~~and in several previously carried out researches (see Table 1), ~~the contributions analysis highlighted that~~ feedstock production and emissions from digestate storage are the main responsible ~~of~~for the environmental impacts for most of the ~~usually~~commonly evaluated impact categories. Therefore, concerning ~~the~~ feedstock production, primary data should be collected also considering the wide geographic and temporal variability of cultivation practices and biomass yield. For this aspect, the use of secondary data affects the reliability of the ~~the~~ results. ~~The collection of primary data for~~With regard to digestate emissions, primary data collection is expensive, hazardous and time-consuming; consequently, the use of secondary data is frequently inevitable. Nevertheless, site-specific data should be used to assess these emissions, as th~~at~~ey are deeply affected by climatic conditions.

6.2 Methodological issue

For what concern the LCA type~~ of LCA~~, although ~~actually~~nowadays aLCA is the most applied, in the future, the cLCA will be probably mo~~st~~re widespread in the future. The environmental aspects related to agricultural AD plants will be evaluated more and more ~~evaluated~~ considering not only their absolute impact (evaluable with an aLCA) but also their effect on the local production systems and, in particular, on the marginal technologies that ~~the~~ biogas plants could displace/affect. Wh~~en~~ith aLCA, allocation is performed among the different products and co-products. Regarding the digestate, the accounting of credits evaluated considering the replacement of mineral fertilizers production ~~based~~ based on~~onaccording~~ the digestate content in N, P and K should be avoided. First, because the digestate is frequently applied on soils that, due to the application of animal slurries for several years~~ of animal slurries~~, do~~esn't~~ not require fertilization with P and K and, secondarily, because the efficiency of mineral fertilizers is considerably higher respect to the one of ~~the~~ digestate.

~~Regarding the functional unit, above all~~ W~~w~~hen the outcomes of ~~the~~ LCA studies have to be compared with ~~the~~ results of ~~previously carried out~~other researches, the selected FU should be:

- for plants fed also with energy crops:~~,~~ the produced electricity if ~~the~~ biogas is used into an ICE CHP or ~~to~~ the volume of produced methane in case of plants where ~~the~~ biogas is upgraded to biomethane;
- for ~~the~~ plants ~~only~~ fed only with waste (e.g., animal slurry):~~,~~ the mass of digested feedstock.

Finally, the choice of the LCIA method should be carefully evaluated considering the goal of the study and, in particular, the assessed impact categories. When the study aims to assess AD plants fed by energy crops, a LCIA method able to properly ~~assess~~quantify the impact categories affected by fertilizer related emissions (e.g., acidification and eut~~h~~rophication~~s~~) should be selected. If the study compares biogas plants ~~with~~of different size, to highlight the plants differences ~~among the plants related to~~ in term of building and maintenance, LCIA methods such as Recipe, CML and ILCD should be adopted.

~~6~~7. Conclusion

Anaerobic digestion of agricultural feedstock is considered to have a high saving potential with respect to greenhouse gas emissions. However, beyond that, other environmental implications of biogas production are still unclear despite quite a few life cycle assessment ~~(LCA)~~ studies. The results of the review highlights that the goal, scope, life cycle impact assessment (LCIA) methodology, feedstock and geographical regions of the LCA studies on biogas vary widely. These differences, including the approach to solve mutifunctionality, determine the obtainment of very different results among the studies, making it difficult to compare them and make generic conclusions on the environmental sustainability of biogas.

Thanks to its flexibility and multi-functionality, the anaerobic digestion technology can play a relevant role in renewable energy production by transforming several biomass streams into useful products, contributing to closing of organic matter cycles. However, this multifunctional feature is also a demanding issue for a consistent sustainability assessment of biogas systems. No general consensus has been reached regarding the optimal functional unit, the allocation of the environmental impact between co-products, the definition of the system boundary, or how to model the carbon cycle of biomass.

Environmental LCA evaluations are increasingly relevant for marketing strategies, managing supply chains, and politic ~~decision making~~decision-making. A higher level of transparency and a harmonisation of the preparation of biogas LCAs are needed to improve the comparability of LCA study results. There is a need to promote the development of common guidelines specific for biogas systems to assess and communicate their environmental performance.

The outcomes of the ~~4~~ four evaluated case studies highlight that the best environmental results are obtained with plants fed with agricultural waste instead of energy crops. Covering the digestate storage ~~tanks~~ as well as fully exploiting the surplus heat are effective mitigation solutions. Finally, the capital goods related to the AD plants should be included in the system boundary in particular for small AD plant where their impact is high.

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Author contributions

All the authors conceived the work, JB and CS reviewed the LCA studies; JB collected, processed the data regarding the case studies, JB, AF and CS wrote the paper.

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Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable

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Abstract

Anaerobic Digestion (AD) has been recognized as a viable solution to produce renewable energy and to reduce global warming especially when secondary feedstock and/or wastes are used. Several LCA studies analysed the environmental performances of biogas production systems. The results of this review highlight that the goal, scope, life cycle impact assessment (LCIA) methodology, feedstocks and geographical regions covered by the studies vary widely. Most studies are based in Europe, several in China and few in South and North America and in Africa.

To better highlight how the choices on the feeding mix, the digestate storage, the surplus heat valorisation as well as the plant size can affect the environmental performances of agricultural AD plants four plants have been analyzed in this study. The results suggest that the energy crops production and the operation of anaerobic digesters, including digestate emission from open tanks, are the main contributors to the impacts from biogas electricity. This entails that it is environmentally better to have smaller plants using slurry and waste rather than bigger plants fed with energy crops. Recovering heat waste as well as covering of digestate tank would improve significantly the environmental sustainability of biogas electricity, and particularly the global warming category.

Keywords

Renewable energy, environmental impact, life cycle assessment, mitigation strategies, biogas, comprehensive review.

1. Introduction

Anaerobic Digestion (AD) has been recognized as an effective solution to reduce greenhouses gases (GHG) and to produce renewable energy especially when secondary feedstock and/or wastes are digested [1-3]. In fact, AD plants can be fed with a wide range of feedstock. The AD of the organic fraction of municipal solid waste (OFMSW) [4-6], sewage sludge [7-10] and food waste [11-13] is by far one of the most rational solutions to manage this waste, this matrix is of the most used feedstock for biogas production: nevertheless, for what concern the agricultural and agro-industry sectors the suitable feedstock are several. Besides energy crops (e.g., cereals, grass, mischantus, switchgrass and sunflower) specifically cultivated, animal slurry and manure as well as waste (e.g., pomace, vegetable residues, tomato peel and skin, slaughterhouse waste) and by-products (from winery and distilleries, from biodiesel production, from cereal mill) of the main agro-industries can be digested [14-16].

In this context, in the last years, thanks also to favourable public subsidy framework, several agricultural AD plants have been built in particular in Europe [15]. This rapid expansion in Europe is largely due to the feed-in-tariffs (FiT) schemes available in 29 countries [17]. For example, in Italy, the electricity produced by AD plants smaller than 1 MW and built before the 2013 is paid 280 € per MWh [18-19]. In the UK, the subsidies are significantly lower, ranging from 130-210 €/MWh, depending on the plant size [17]. Production of biogas is expanding rapidly in Europe. According to EurObserv'ER [20], about 14.9 million tonnes oil equivalent (Mtoe) of biogas primary energy was produced in the EU during 2014, which equates to 6.6% growth on the previous year. However, despite this grow, the same sector trend of slower growth than in previous years, because of the biogas policy U-turns made by the European Union's two major producer countries, Germany and Italy. Germany, with 8726 AD plants, 3905 MW of installed capacity and 29 TWh of electricity produced, is the largest producer of biogas, not only in Europe but in the world [20]. Italy follows at 8.2 TWh of electricity produced by 1700 AD plants in 2014 (+10% respect to 2013) with the total installed capacity of about 1000 MW [18, 20]. In Austria, about 400 agricultural AD plants are currently running with an installed electric capacity of 107 MW [21].

In order to assess the environmental impacts that are associated with producing and utilizing biogas as an energy carrier, the method of Life Cycle Assessment (LCA) can be applied [22-23] (ISO, 2006). Several LCA studies in Europe and worldwide focused on environmental assessment of biogas production systems. This should provide a solid knowledge base for both policymakers and engineers to improve the efficiency of such systems and reduce their environmental impacts. At the same time, comparing different LCA studies can be challenging due to differences in scope and a lack of documentation. Fusi et al. [16]

analyzed 26 different studies focused on AD plants and found that only five have considered a full suite of impacts normally included in LCA evaluation; among these studies the goal, scope, life cycle impact assessment (LCIA) methodology, feedstocks and geographical regions covered by the studies vary widely making difficult the comparison of the results. Hijazi et al [15] carried out a review focused on agricultural biogas plants in Europe and considered a small number of LCA studies (only 15). There is a lack of a comprehensive review with a comparison of all the LCA studies focused on agricultural AD plants around of the world considering both methodological and operational aspects.

The aim of this study is twofold: first, to perform a review of the LCA studies carried out in the different countries focusing on agricultural AD plants and second, to present the results of selected case studies in order to highlight how the environmental results are affected by methodological choices as well as by operational aspects.

2. Materials and methods

The goals of this review are:

- Summarize the current knowledge of the methodology of LCA studies of agricultural biogas systems,
- Systematically compare different LCA-studies of agricultural biogas systems to get a rigorous review,
- Make a synthesis of the achieved results and conclude on the status of environmental impacts associated with agricultural biogas plants worldwide in order to identify measures for its reduction.

To this aims scientific manuscripts were selected in Web of Science™ databases by combing the following keywords “Life Cycle Assessment”, “LCA”, “anaerobic digestion”, “biogas”, “carbon footprint” and “GHG emissions”.

Among the 105 studies identified, 68 were reviewed in detail according to the following criteria:

- To analyse the environmental performance of the AD process carried out in agricultural biogas plants is the main aim of the study;
- The feeding of the AD plants should involves at least one of the following feedstock: energy crops, animal waste, other agricultural by-products and waste from agro-industry; therefore, studies dealing only on municipal solid waste AD for biogas production were not considered;

- To reflect the actual state of the art and recent developments as well as the application of updated LCA method only studies published in the last 15 years were included;
- Only studies published in peer-review scientific journals were considered, conference papers, Ph.D. and Master Theses were not taken into account;
- The study must include at least the impact category Global Warming Potential (GWP);
- Studies must be based on defined methods such as LCA [22-23] (ISO 14040 and 14044), carbon footprint [24] (ISO, 2013) or EU Renewable Energy Directive RED [25] or the applied methodology must be fully explained.

3. Review results

The main review results are reported in **Table 1**. Among the 69 analysed studies, 56 referred to agricultural AD plants built in Europe, 6 in Asia, 4 in North-Centre America, 2 in South America and only 1 in Africa.

Table 1 - around here.

3.1 Operational aspects

3.1.1 Number of AD plants analysed and their size

Although in most of the studies (34) only one AD plant was analysed, in others more than one agricultural biogas plants were evaluated, differentiated for feeding, size and technological aspects. The plants have a capacity below 1 MW, with the majority being around 500 kW and only few below 100 kW.

3.2.2 Feedstock

A wide variety of feedstock was used to feed the plants; (see **Table S1 in Supplementary Materials** for more details) 4 typologies can be identified:

- Energy crops, crops specifically cultivated for biogas production. Among these, the cereals were by far the most used. However, in particular in Countries where public subsidies are granted for electricity and/or biomethane production by biogas (e.g., Germany, Italy and UK), the agricultural AD plants are fed mainly with cereal silages. Although also considerable amount of animal effluents (slurry and manure) are digested, the main fraction of produced biogas arises from cereal silages. Among these, the maize was the most used thanks to its high specific biogas production [98], storability and biomass yield [99]: in 38 of the 69 analysed LCA studies maize silage was digested. This kind of feedstock is usually fed into AD plants characterized by medium-large size (electric power >300 kW) in co-digestion with other feedstock characterised by high moisture content (e.g., animal slurry, whey). Besides cereals, also miscanthus, sugar beet, hemp, clover and sunflower were tested. In particular, Blengini et al [32] identify the miscanthus as the most sustainable if only GWP is evaluated;

- Animal slurry and manure from pig and cattle were the most commonly digested due to the diffusion of this kind of livestock activities; nevertheless, also poultry manure was used. As opposed to energy crops, this kind of feedstock was mainly used in small AD plants where mono-digestion is performed. Several studies highlighted how AD plants fed with animal slurry and manure achieve better environmental performance compared to the ones fed with the energy crops. This is possible because, being the slurries and manure a waste of other activities, no environmental load is associated with them; moreover their digestion was frequently associated with credits for the avoided emissions of their traditional management in open tanks [29, 58, 59, 60, 64,100]. Nevertheless, the environmental performance of AD plants fed with animal effluents (above all the liquid ones, such as pig slurry) strongly depends on the transport distances, that should be minimized [29, 101, 102].

- Agricultural and agro-industry by-products and wastes, this group includes feedstock characterized by great variability in terms of dry matter content, specific biogas production, origins, availability and seasonability. Both agricultural and agro-food industry by-products and wastes are available in specific seasons of the year (usually after the harvesting) but, differently from the agricultural ones, available in small amounts in several points of the territory (e.g., straw), the agro-industrial ones are concentrated close to the processing plants (e.g., winery wastes). The spreading of feedstock on the territory, besides logistics issues, involves also high environmental impacts related to the transport distances.

The most frequently digested agricultural by-products and waste were straw (usually after specific pre-treatment), tops and leaves of sugar beets, while the agro-food ones are distiller's waste, rapeseed cake, cheese whey, milk fodder, bakery residues, winery waste, sugar beet pulp, tomato seeds and peels, fruit residues, fatty residues, oil seed residues and potatoes residues. In some studies only generic information are reported about the digested feedstock (e.g., agro-industrial wastes or biodegradable matrixes) [39].

3.2 Methodological aspects

3.2.1 Type of LCA study

Depending on the goal of the study two types of LCA can be performed: attributional LCA (aLCA) and consequential LCA (cLCA). aLCA describes the relevant physical input and output flows entering and exiting from a product system, whereas cLCA defines how these flows might be modified in response to a decision or a change [82, 103, 104]. aLCA is useful for identifying systems with important impacts, whereas cLCA is useful for evaluating the consequences of individual decisions [84]. The consequential life cycle assessment (cLCA) is a “prospective” method [75], it is used to identify the marginal technology substituted new technology under evaluation. In contrast to the attributional approach, where average (not marginal) technologies are used, the cLCA approach is applied to obtain information about the environmental impact changes related by a change in demand or in the output of the functional unit [75].

In the cLCA approach “system expansion” and “substitution”, also called “system enlargement” or “crediting” is used to solve multi-functionality (processes with more than one output product) [103]. On the contrary, in aLCA allocation is used to solve multi-functionality (see. Section 3.1.5).

In many LCA studies about energy generation from AD plants, there was no differentiation between aLCA and cLCA and frequently allocation and system expansion were mixed [75]. According to Reinhard and Zah [105], in cLCA the environmental results depend on the environmental scores of the marginal technology replaced rather than on local production factors. In other words, the marginal technology assumed to be affected by AD plants is the most important factor in the results.

The review results confirmed the findings of Rehl et al., [75] and Reinhard and Zah [105]: cLCA was less carried out respect to aLCA (only 10 studies out of the 69 analysed) and the majority of the studies performed aLCA but mix allocation and system expansion were used to solve the multifuntionaly issue. aLCA is by far most applied respect to cLCA mainly because it is usually focused on the identification of the environmental impact of few AD plants and it requires a less comprehensive inventory in particular with regard to the marginal technologies affected by the AD plants.

3.2.2 Functional unit (FU)

ISO 14044 recommends that ‘‘the functional unit shall be consistent with the goal and scope of the study’’. However, the objectives of biogas LCA studies and the functions provided by biogas systems are diversified and therefore functional units are numerous. According to their main function, the agricultural AD plants analysed in the reviewed studies can be divided into:

- plants designed with the purpose to produce energy or energy carriers (e.g., biomethane) for their subsequent selling. For these AD plants the most used FU are: (i) the delivered energy, usually electricity but also thermal energy or a mix of both, (ii) the produced volume of biogas or biomethane, (iii) the energy content in the energy carriers.

- plants built for treatment of waste (e.g., animal effluents, agro-industrial residues) in which the production of energy is only a secondary aim because the main function of the system is the improvement of the traditional management of these wastes. In this case, the FU is usually related to the amount of waste treated (e.g., 1 ton of slurry) or to the main product generated from the production system from which the waste arises. Gutierrez et al. [50] assessed the environmental effect of the AD of animal slurry for 1 pig of 120 kg in Cuba; Bacenetti et al [30, 31] for the digestion of tomato puree by-products (peels and seeds) and cow slurry, expressed the results for 1 kg of tomato puree and for 1 kg of milk, respectively.

Some LCAs used case-specific, energy output-related functional units, such as the annual electricity and heat consumption of a village of 150 households [57].

In the 69 studies reviewed in Table 1, the following FU was adopted: the produced electric energy (23 studies), the cogenerate electricity and heat (6 studies), the volume of biogas or biomethane (5 studies), the energy contained in the biomethane (10 studies), the amount of digested feedstock (8 studies), the main process from which the digested waste arise (e.g., milk, tomato purea, meat) (3 studies), mixed and site specific units (e.g., 1 year of farm operation, the volume of the digester, in the remaining studies). The wide variability of FU, although justified by the different aims of the reviewed LCA studies, makes the comparison among the results of the different studies not always possible.

3.2.3 System boundary

Among the LCA studies reviewed, the system boundary (SB) varies mainly according to the feedstock used to feed the digester and to the selected functional unit. When energy crops are digested, the SB encompass also the crop cultivation while when only animal waste and/or by-products from agro-industry are used the SB focuses only on anaerobic digestion and biogas treatment/use. For LCA studies focused only on the biomethane production [26, 26, 63, 66, 74, 106, 107] a “gate to gate approach” was used, in particular if different upgrading technologies were compared.

Both for energy and biomethane production, the distribution stage was usually excluded from the system boundaries.

Several capital goods are employed over the AD production process; tractors and equipment are needed for crop cultivation and/or feedstock transport, building such as silos or tanks can be used for biomass storage while, at the AD plant, digesters, tanks as well as devices for biogas treatment upgrading and utilization are always present. Manufacturing, maintenance and disposal of these goods is associated with an environmental load.

Regarding the inclusion in the system boundary of capital goods three different approach can be highlighted: (i) exclusion of capital good both at field level (energy crops cultivation) and at AD plant level; (ii) exclusion only of capital goods at AD plant level; (iii) inclusion of these goods at the two levels. Usually when energy crops were used to feed the digesters, capital goods for field operations and biomass transport were considered while the ones at AD plant level were excluded. The exclusion is supported by the low impact related to capital goods for some impact categories. For example, according to Rapport et al [108] and Hartman [109], GHG emissions related to infrastructures represent less the 4% of global emission through the whole process while, according to Bühle et al. [110, 111], the supply of infrastructure such as buildings, machinery, and roads contribute less than 10% to the total energy input over a time span of 20 years.

The exclusion of capital goods from the system boundary was the most frequently choice; only 19 of the 69 reviewed studies included the capital goods both at the field and the AD plant level.

Land Use Change (LUC) was taken into account in only 7 studies; usually LUC was not accounted considering that the area where energy crops is cultivated were already previously grown with this kind of crops. The LUC (direct – dLUC and indirect – ILUC), when taken into account, strongly affects the GWP impact category [82]. Hamelin et al. [52], who compared six different feedstock, highlighted that the maize scenario is the only one giving rise to a net global warming impact. This result was mostly due to the LUC. Unfortunately, depending on the assumptions made, the value considered for LUC widely varies. For example, in Hamelin et al. [52], the value considered (equal to 18 t CO_2 eq.· ha^{-1} displaced·y^{-1}) appears in the middle-high range. Lund et al. [112] reported a range of 10–28 t CO_2 eq.·ha^{-1} displaced·y^{-1}, while Meyer-Aurich et al, [64] considered a figures of 2.6-10 t CO_2 eq.·ha^{-1}·y^{-1} (for turning hectares of German grassland to cropland production).

3.1.4 Inventory analysis and data sources

Surprisingly, concerning the foreground data[1], more than half of the reviewed studies (38) are carried out using mainly secondary data coming from literature and databases (above all ECOINVENT®). Only 14 were completely based on primary foreground data and referred to literature and databases only for background data.

Primary data are usually collected via questionnaires and interviews to:

1) The farmers, who provide information on feedstock production; and
2) AD managers and operators, for data on energy production and consumption and daily feedstock requirements.

Secondary data were usually used for the assessment of emissions related to digestate application and biogas combustion in the CHP engine as well as for the evaluation of the credits arising from digestate use as organic fertilizer and from avoided traditional slurry management.

3.1.5 Multifunctionality issue

The biogas, generated together with the digestate during the feedstock digestion, can be upgraded to biomethane or be fed in a CHP ICE to produce electricity and heat (**Figure 1**). The sharing of the environmental impact among the different products, co-products and byproduct is a methodological issue that can be faced by means of allocation as well as by the system expansion [75].

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[1] Foreground data refer to foreground system i.e. core processes of the analysed production system in which actions can be directly taken and where direct measurements can often be carried out (primary data). Foreground data are distinguished from background system where usually no modification and no data measurement are possible.

Figure 1 around here

In the allocation approach, the environmental burden is divided among the main product, coproducts and by-products using physical properties such as mass, energy, exergy or economic value ratios. According to ISO standards [22, 23], allocation should be avoided by means of system expansion. In the reviewed LCA studies, the system expansion approach was usually carried out for the digestate. To solve the multi-functionality related to the cogenerated heat, two main trends were found in the reviewed studies: (i) when the heat is wasted, all the environmental impact is ascribed to the electricity, (ii) when the heat is recovered, the "system expansion" and the allocation based on exergy content were the usually used approaches. In Rana et. al. [73] and Manninen et al. [63], consistently with the RED methodology, the co-products allocation procedure was performed using an energy-content based criterion to account for the digestate fractions not reused within the system and modelled as co-products. The allocation procedure was based upon the Lower Heating Value (LHV) values related to biogas, and both Solid Fraction and Liquid Fraction of the digestate.

According Manninen et al. [63], it is questionable whether the RED calculation rules are suitable for a multifunctional production system such as biogas production system. Indeed if the co-product generated (e.g. digestate) has an energy content of zero, and it is not used for energy production, energy allocation is not the best method to use.

Concerning the accounting of environmental benefits arising from the use of digestate as fertilizer, different approaches were identified. Some studies [16, 29, 45] consider that the digestate is used to fertilize the energy crops in a close loop where only indirect environmental benefits (derived by the reduction of chemical fertilizers needing) are accounted. However, in the majority of the studies, a substitution approach was considered: the digestate, depending on its nutrient content, is supposed to avoid the production of mineral fertilizers and, therefore, the environmental impact of chemical fertilizers production. The latter is credited to the AD process. For the N, P and K in the digestate, different mineral fertilizer equivalents (MFE[2]) were considered. Usually for P and K the MFE is equal to 100% while it is lower for N depending on its NH_4 component [87]. Only few studies accounted the credit for digestate considering the real needing of the soil; for example Hamelin et al. [53] account a MFE equal

[2] MFE, measure of the efficiency of the nutrient in the digestate to substitute an equal amount of nutrient from mineral fertilizer.

to 0% for P and K in Danish soils where, due to slurries application for several years, the level of phosphorous and potassium is adequate for cereal cultivation even without digestate application.

Due to P accumulation in the soil [113], the accounting of the digestate credits for the replacement of P fertilizers should be avoided, in particular for soil fertilized with animal slurry and manure for several years.

3.1.6 LCIA methods and evaluated impact category

The greatest variation among the studies was found in the number of impacts considered and the methodologies used to estimate them. The former range from one to 18 and the latter cover almost all known LCIA methods, including the EcoIndicator 99, CML 2001, Impact 2002+, ReCiPe and ILCD methods. The Global Warming Potential (also called Carbon Footprint or Climate Change impact category) is the only impact evaluated in all the reviewed studies, however also for this impact category different methods were used for the assessment: IPCC 2007 [114], RED as well as the standard ISO/TS 14067:2013 [24].

4. Discussion

4.1 Main results

For what concern the global warming potential, the agricultural AD plants evaluated in the different reviewed studies usually achieved better environmental performances compared to the reference systems based on fossil fuels (e.g., natural gas, electricity from coal or natural gas, etc.). For the studies in which the electricity is selected as functional unit, the Global Warming Potential (GWP) results, reported in **Figure 2** showed a huge variability. In particular, the highest value (0.55 kg CO_2eq/kWh) was recorded by Siegl et al. [79, 80] for small AD plants (50-150 kW) fed with cereal silage in Austria while the lowest GWP (-1.72 kg CO_2eq/kWh) was reported by Boulamanti et al. [35] for plants fed by manure with covered digester storage tanks. Although, this variability was mainly due to the assumptions made (e.g., methane losses for leakages, emissions from digestate, allocation) and to the system boundary (e.g., avoided emission from traditional manure management, avoided emission from the composting of agricultural residues and other wastes) some general conclusions can be drawn:

- Respect to electricity from fossil fuel, the electric energy produced in the agricultural AD plants showed, also in the worst cases [35, 75, 79, 80], lower GWP;

- GHG emission savings (negative values for GWP) were achievable only if credits for mineral fertilizer substitution and/or heat and avoided traditional manure management were considered;
- AD plants fed mainly with animal slurry and agricultural and/or agro-industry by-products and waste performed better than the ones fed with cereal silages;
- covering the tanks for digestate storage and exploiting the surplus heat are the most feasible solutions to improve the GWP of agricultural AD plants [16, 28, 75].

Figure 2 around here

Surplus heat valorisation deeply affects the environmental performances of electricity production form AD plants. In the study carried out by Ravina and Genon. [74], the direct combustion of biogas in ICE CHP unit was the most favourable solution in terms of GWP only if surplus heat is used. For plants fed only with cereal silage, sustainability was strongly reduced (and in some cases can come less) if the cogenerated thermal energy is not fully exploited [4, 71, 74, 101, 102].

Chevalier and Meunier [39] demonstrated that biogas co- or tri-generation was always environmentally friendly with respect to global warming and resources depletion as long as the distance for collecting crops from farms is not too far (20–50 km). Tri-generation, also referred to as CHCP (combined heating, cooling and power) allows greater operational flexibility extending the use of co-generation when there is no need for heat.

Concerning the other impact categories and, in particular, eutrophication and acidification, the main differences were found between the AD plants fed with energy crops and the ones fed with feedstock other than energy crops. When energy crops were used, the electricity from biogas scores higher in the eutrophcation and acidification categories than the electricity from fossil fuels [16, 45, 29, 101]. This was mainly due to the use of fertilizers (and to their related emissions such as N and P compounds into air, soil and water) during crop growing.

Regarding the biomethane production, the comparison among the different studies is difficult due to the selection of different functional units. According to several studies, biomethane production represents a viable alternative to fossil fuels, in particular for transports. In particular, a GHG saving when biomethane is used for transports was reported by Poeschl et al. [71, 101, 102] (1.15 kgCO_2eq/kg biomethane) and by Power and Murphy [115] (between 0.017 kg/MJ and 0.02 kg/MJ depending on the feedstock). The GHG performance of the different crop-based biomethane systems was calculated by

Börjesson et al. [33]: the results range from 22 to 47 $kgCO_2eq/GJ$ biomethane when credit of increased soil organic carbon (SOC) content was excluded, and from −2 to 45 $kgCO_2eq/GJ$ biomethane when it was included. Berglund and Borjesson [34] included in the calculation of life cycle emissions of GHGs the changes in soil organic carbon (SOC) content. Changes in SOC due to crop residues and digestate added to the soil were accounted for using the Introductory Soil Carbon Balance Model (ICBM). In this study, ley crop-based biogas systems led to a "negative" net contribution of GHG emissions due to the significant SOC accumulation in these cultivation systems.

4.2 Contribution analysis

The contribution analysis, aimed at identifying the environmental hotspots of the system investigated, was not performed in all the reviewed studies.

Feedstock production and transport represented the main contributors to the environmental impact in particular when energy crops were used or when by-products and waste were transported over long distances. Energy crops were recognized as one of the main environmental hotspots in particular for impact categories associated with N and P emissions into air, soil and water. When only energy crops were fed into the digesters [17, 45, 29, 60-62] and the biogas was fed into a CHP internal combustion engine (ICE), the environmental impact of the cogengerated electricity was close to the one of electricity from fossil fuel for what concern GWP and it is higher for eutrophication and acidification.

Methane leakages from digesters and devices for biogas treatment as well as un-combusted CH_4 in the exhaust gases strongly affect for GWP and, by a lower extent, ozone depletion. A minor role on the environmental impact was played by the other inputs used for the AD plants (e.g., lubricating oil for the CHP ICE, chemicals for biogas desulphurization, etc.) as well as by the electricity consumed by all the different devices (mixers, pumps, etc.).

As explained in section 3.1.2, the contribution of manufacturing, maintenance and disposal of digester and CHP it was not always included in the system boundary. This exclusion is not justified, in particular for small AD plants and for impact categories related to the consumption of metals and fossil resources are assessed. When only GWP is evaluated, the impact of capital good can be neglected for medium-large AD plants (e.g. with an electrical power of the CHP > 500 kW) [108, 110, 111, 116] but in all the other cases (e.g., small plants and several environmental impact considered) the construction materials have to be taken into account. For small plants (CHP ICE with power below 300 kW), the contribution of capital goods to the total impact is in fact higher than for larger plants. Furthermore in some studies [79, 80], the digesters of small plants are made of steel, which needs more resources than a fermenter made of concrete. Furthermore, small CHP engines often show a comparatively low electrical efficiency than bigger CHP (e.g., for CHP ICE of 1 MW of electrical power the electrical efficiency ranges between 40 to 41% while, for smaller plants, it is considerable lower: 33-35% with 200-300 kW of electrical power), this makes the results per kWh of electricity higher in all impact categories for smaller plants.

5. Case studies

In this section, the results of 4 case studies are reported to better highlight how the choices on the feeding mixture, the digestate storage, the surplus heat valorisation as well as the plant size can affect the environmental performances of agricultural AD plants. In more details, the environmental performances of 4 agricultural AD plants located in Italy were assessed.

5.1 AD plants description

The 4 AD plants are all located in Northern Italy. This region, thanks to intensive livestock activities together with proper pedo-climatic conditions for the production of cereal silages, is one of the most important European area for biogas production. In Piedmont, Lombardy, Veneto and Emilia-Romagna (Northern Italy) are located approximately 1000 agricultural AD plants, which represent about ¾ of the Italian agricultural biogas plants [18].

All the 4 AD plants are fed with agricultural feedstock and produce biogas that is used, after being dehumidified with a chiller and desulphurised with a scrubber, in CHP ICE. The produced electricity is fed into the national grid while the cogenerated head is only partially used for digester heating; surplus heat is wasted. Electricity consumed for operating the plants (mixers, pumps, scrubber, chiller, etc.) is taken from the grid. In all the 4 AD plants, the digestate is stored in open tanks and it is used as organic fertilizer for energy crops or for fodder production. In AD plant B, the digestate is partially separated, using a screw separator, into liquid and solid fraction. The first is used to dilute the dry matter concentration inside the digester while the latter is used as organic fertilizer.

5.2 Functional unit and system boundary

The main function of the AD plants is to produce energy and therefore the selected functional unit (FU) is 1 kWh of electricity. As clarified in section 3.1.1 the generated electricity is one of the most used FU for agricultural AD plants in particular when they are fed with energy crops.

Figure 3 summarizes the production process for the 4 different AD plants. The environmental assessment has been carried out applying a "cradle to grave" approach. Consequently, all the processes involved in the electricity production, from the extraction of raw materials needed for energy crops cultivation and AD plant construction to the disposal of waste and infrastructures, have been considered in the system boundary. No environmental impacts are considered for animal slurries as they are waste. The heavy metals contained in the animal slurries have been excluded from the system boundary as they are affected by the AD treatment. The heavy metals emitted into the soil through the application of the digestate are the same as if he animal slurry were used.

Figure 3 around here

5.3 Inventory data

Site-specific data were directly collected by means of surveys and interviews with farmers and AD plant managers. In more details, primary specific data concerning inputs (diesel fuel, feedstock, electricity, heat, sodium hydroxide and lubricant oil) and outputs (biogas, digestate, heat and electricity) were supplied by the AD plant manager and they are referred to the year 2015.

Regarding the energy crops cultivation, primary data refers to biomass yield, transport distance and silage losses. Maize silage was cultivated considering two different cropping systems: single crop and double crop. The recorded silage yields were:

- For maize, 66.0, 68.0, 49.5 and 55.1 t/ha for plant A, B, C and D, respectively;
- For triticale 34.5, 36, 34.5 for plant A, C and D, respectively.

Additional information about inputs (digestate, fertilisers, pesticides, water and diesel fuel) and field emissions derived from fertilisers application were taken from previous studies carried out in the same area and based on primary data [29, 117-120]. Detailed information about cereal crops cultivation is reported in **Table 2**.

Table 2 around here

Fugitive methane losses from digester and from CHP engine were considered equal to 2% in accordance with Dressler et al. [45].

Within the application of any type of fertilizers (organic and mineral), derived field emissions were also estimated. Nitrogen-based emissions (ammonia, nitrous oxide, nitrogen and nitrate) were calculated with factors provided by Brentrup et al. [121]. Phosphate emissions to water were estimated according to Nemecek and Kagi [122].

Emission of methane and ammonia from digestate storage in open tanks have been assessed in accordance with the values reported by Edelmann et al. [123]; in more details these emissions are equal to 8.9 kg/MWh for CH_4 and 0.23 kg/MWh for NH_3.

Emissions associated with the avoided conventional management of animal slurry (methane, ammonia and nitrous oxide) as well as the emission from digestate were calculated with the factors provided by Amon et al. (2006) [124] for cattle slurry and Wang et al. [125] for pig slurry. Considering that, the digestate is applied as organic fertilizer during energy crops production or during the cultivation of fodder used to feed pigs and cattle no additional environmental credits were taken into account.

Combustion emissions derived from the CHP ICE were taken from NERI [126].

Finally, background data regarding the production of all required inputs such as diesel fuel, sodium hydroxide, lubricant oil and electricity, fertilisers as well as capital goods (construction materials, their transport and landfilling) were taken from Ecoinvent® database [122, 127-130].

A life span of 20 and 10 years has been considered for the digesters and for the CHP engine, respectively [16] (Fusi et al., 2016). Since the data for construction materials for the digesters and CHP engines in Ecoinvent correspond to a different plant size (800 m^3 for the digester and 160 kW of 1000 kW for the CHP engines), the environmental impacts from their manufacture have been estimated by scaling up or down to the sizes of the AD and CHP plants considered in this study. This has been carried out following the approach used for cost estimation in scaling process plants [16-17].

The main inventory data are reported in **Table 3**.

Table 3 – around here

5.4 Impact assessment

The environmental impacts have been evaluated using the composite midpoint LCIA method recommended by the International Reference Life Cycle Data System (ILCD) Handbook [97]. The following impact categories were considered: global warming potential (GWP), ozone depletion (OD), particulate matter (PM), human toxicity (HT), Photochemical ozone formation (POF), terrestrial acidification (TA), terrestrial eutrophication (TE), freshwater eutrophication (FE), marine eutrophication (ME), freshwater ecotoxicity (FEx), and mineral and fossil resource depletion (MFRD).

5.5 Environmental results

Figure 4 shows the results of the environmental impact assessment for the 4 AD plants. The different inputs and outputs were gathered as follow:

- Feedstock production and transport includes the cereal silage production (when occurs) as well as silage and slurry transport;

- Infrastructures considers the construction of the AD plant (digesters and CHP engine) and its maintenance and disposal;

- CHP emissions in air by the exhaust ICE gases;

- Digestate emissions in air;

- Avoided emissions from slurry, which accounts the avoided emissions arising from traditional slurry storage in open tanks;

- Others, involves the methane losses as well as the consumption of electricity, NaOH, water and lubricating oil.

Figure 4 around here

5.5.1 Global Warming Potential

AD plants fed with cereal silages show higher GWP respect to the ones fed only with animal slurry. In more details, Plant A, where only maize and triticale silages are used, shows an emission of GHG comparable with the one of Italian electricity mix [16]. Electricity from plants C and D, where cattle and pig slurry are fed to the digesters, involves a GHG savings (-0.37 and – 1.44 kg CO_2eq/kWh in plant C and D, respectively). From one side the digestion of animal slurry allows to produce biogas by valorising a waste without environmental burden and, from the other side, it involves considerable credits due to the substitution of the traditional slurry management (and related emissions in air - above all CH_4 and NH_3). Feedstock production and digestate emissions are the main environmental hotspot for this impact category while infrastructures and CHP emissions play a minor role.

5.5.2 Ozone depletion

Remarkable differences can be highlighted among the 4 plants; compared to plant A, plant D shows a lower impact (-44%). The main environmental hotspots are feedstock production and transport, for the plants fed with cereal silages, and methane losses. The infrastructures, responsible for a negligible impact for medium and large plants (<5%) represent about 10% of the overall impact for the small plant (Plant D).

5.5.3 Human toxicities

For both Human toxicities (Cancer effects – HTc and no cancer effects - HTnoc), bigger plants show slightly the worst performance but the differences among the four biogas plants are small in particular for HTnoc. For what concern the contribution analysis:

- in HTc, feedstock production and transport and infrastructure are the hotspots; overall they contribute from 76 to 83% to the environmental load. The impact of feedstock is high for medium-large plants fed with cereal silages (from 47 to 59%) and lower for the small plant D (19%). On the contrary, the impact of infrastructures is predominant in plants fed with slurry and characterized by high specific digester volumes (36% and 56% in plant C and D, respectively) and less important in the other plants fed mainly with cereal silages (24% and 26% in plant A and B, respectively);
- in HTnoc, the key-aspects are the CHP emissions (57-60% in all the AD plants) and, again, the feedstock (31-40%).

5.5.4 Particulate matter, terrestrial acidification, eutrophications, freshwater ecotoxicity

All these impact categories show a similar trend: feedstock production and transport is by far the main hotspot when cereal silage is used. Plant D, fed only with animal slurry, has considerably better results: respect to plant A (the worst) it scores 4.3 times lower for PM, 6.3 for TA, 7.3 for TE, 65.4 for FE, 7.2 for ME and 34.7 for FEx. The role of emission from digestate, although minor respect to feedstock production and transport, cannot be neglected in PM and TE, mainly due to the ammonia emission into atmosphere.

5.5.5 Photochemical oxidant formation

As for GWP also for this impact category, the digestion of slurry involves environmental credits; nevertheless, these credits allow to offset the environmental impact only for Plant D. The environmental hotspots are feedstock production and transport, methane losses and digestate emissions while the infrastructures play a minor role.

5.5.6 Mineral, fossil & renewable resource depletion

For MFRD, the result ranges from 0.49 to 1.20 mg Sb eq./kWh, AD plants fed with cereal silages have similar results while plant D performs better. Feedstock production and transport is the main hotspot (>90% for plants A, B and C and 76% in plant D); for the smaller plant (Plant 4), the infrastructures are responsible for 12% of the impact. The impact of CHP and digestate emission is negligible in all the AD plants.

5.5.6 Alternative scenarios

To test the robustness of the results as well as to evaluate how the environmental performance of electricity from biogas is affected by different technological solutions and methodological choices, different scenarios were considered:

- covered digestate storage: this scenario involves the reduction of digestate emissions by 80% according to Oenema et al. (2012)[131] as well as the construction of AD plants characterized by covered tanks. To this regard the specific process “Anaerobic digestion plant, agriculture/CH” in the Ecoinvent Database has been used instead of “Anaerobic digestion plant, agriculture covered/CH” process. The impact of covering digestate tanks is reported in **Table 4**; the effects are negligible only for HTc, HTnoc, FE, ME and FEx while is relevant for all the other impact categories. In more details, for GWP, plant A almost halves its GHG emissions, plant B offsets its score and turns to produce benefits while plants C and D expand the magnitude of these benefits. In absolute terms, storing the digestate in covered tanks allows a GHG emission savings ranging from 0.26 kg CO_2eq/kWh in plant D to 0.27 kg CO_2eq/kWh in plant A. The mineral and fossil resource depletion (MFRD) impact increases for all the plants considered due to higher material and energy consumptions related to the building of covered digestate tank.

Table 4 around here

- surplus heat valorisation: in this scenario the thermal energy not consumed for digesters heating is exploited in a district heating and it substitutes heat produced in domestic boiler from natural gas (marginal technology). Three different share of valorisation (25%, 50% and 100%) have been considered.

The results are shown in **Table 5**. When the heat is valorised environmental benefits are achieved in all the impact categories. OD is the environmental impact where the benefits are more evident (impact reduction ranging from 80-85% with 25% of surplus heat exploited to 300-330% with 100% of surplus heat exploited) but also GWP, HTc, POF and MFRD achieve considerable impact reductions. With a full valorisation of surplus heat, GWP is reduced by 10%-46%, HTc by 48-54%; POF by 33-79% and MFRD by 24-35%. The other impact categories (HTnoc, PM, TA, TE, FE, ME, FEx) are less affected by heat valorisation. These impact categories are, in fact, the ones most affected by feedstock production and by the marginal technology.

Table 5 around here

- exclusion of capital goods: in this scenario the impact related to the construction and maintenance of digesters, CHP system and all the other infrastructures characterizing the AD plants (dump, pre storage tanks for slurry) has not been considered. The results for this scenario are reported in **Table 6.** As can been inferred from the table, all plants beneficiate from the exclusion of the impact of capital goods and the best results are obtained in GWP, HTc and MFRD. The construction, maintenance and disposal of the capital goods have a higher impact on small AD plants (e.g., Plant D) while for the bigger plants slightly affect the impact categories except HTc, to which they contribute by XX% .

As highlighted in section 3.1.3, the contribute of infrastructure to small AD plants is proportionally higher because they are fed with feedstock with lower specific methane production and, consequently, the digester specific volume is bigger (19.1 m^3 of digester/kW for plant D and 11.9 m^3 of digester/kW for plant A).

Table 6 around here

6. Future trends in LCA application to agricultural AD systems

Over the years, the application of LCA to agricultural biogas plants allowed to depict the environmental impact related to this renewable energy source as well as to highlight the mitigation strategies that can be undertaken to improve AD sustainability [132]. Nevertheless, there are unsolved challenges and methodological choices that should be harmonized for improving the robustness of LCA results and to make the outcomes of different studies comparable.

6.1 Challenges

As highlighted in the presented case studies and in several previously carried out researches (see Table 1), feedstock production and emissions from digestate storage are the main responsible for the environmental impacts for most of the commonly evaluated impact categories. Therefore, concerning feedstock production, primary data should be collected also considering the wide geographic and temporal variability of cultivation practices and biomass yield. For this aspect, the use of secondary data affects the reliability of the results. With regard to digestate emissions, primary data collection is expensive, hazardous and time-consuming; consequently, the use of secondary data is frequently inevitable. Nevertheless, site-specific data should be used to assess these emissions, as they are deeply affected by climatic conditions.

6.2 Methodological issue

For what concern the LCA type, although nowadays aLCA is the most applied, in the future, the cLCA will be probably more widespread in the future. The environmental aspects related to agricultural AD plants will be evaluated more and more considering not only their absolute impact (evaluable with an aLCA) but also their effect on the local production systems and, in particular, on the marginal technologies that biogas plants could displace/affect. Whith aLCA, allocation is performed among the different products and co-products. Regarding the digestate, the accounting of credits evaluated considering the replacement of mineral fertilizers production based onthe digestate content in N, P and K should be avoided. First, because the digestate is frequently applied on soils that, due to the application of animal slurries for several years, do not require fertilization with P and K and, secondarily, because the efficiency of mineral fertilizers is considerably higher respect to the one of digestate.

When the outcomes of LCA studies have to be compared with results of other researches, the selected FU should be:

- for plants fed also with energy crops: the produced electricity if biogas is used into an ICE CHP or the volume of produced methane in case of plants where biogas is upgraded to biomethane;
- for plants fed only with waste (e.g., animal slurry): the mass of digested feedstock.

Finally, the choice of the LCIA method should be carefully evaluated considering the goal of the study and, in particular, the assessed impact categories. When the study aims to assess AD plants fed by energy crops, a LCIA method able to properly quantify the impact categories affected by fertilizer related emissions (e.g., acidification and eutrophication) should be selected. If the study compares biogas plants of different size, to highlight the plants differences in term of building and maintenance, LCIA methods such as Recipe, CML and ILCD should be adopted.

7. Conclusion

Anaerobic digestion of agricultural feedstock is considered to have a high saving potential with respect to greenhouse gas emissions. However, beyond that, other environmental implications of biogas production are still unclear despite quite a few life cycle assessment studies. The results of the review highlights that the goal, scope, life cycle impact assessment (LCIA) methodology, feedstock and geographical regions of the LCA studies on biogas vary widely. These differences, including the approach to solve mutifunctionality, determine the obtainment of very different results among the studies, making it difficult to compare them and make generic conclusions on the environmental sustainability of biogas.

Thanks to its flexibility and multi-functionality, the anaerobic digestion technology can play a relevant role in renewable energy production by transforming several biomass streams into useful products, contributing to closing of organic matter cycles. However, this multifunctional feature is also a demanding issue for a consistent sustainability assessment of biogas systems. No general consensus has been reached regarding the optimal functional unit, the allocation of the environmental impact between co-products, the definition of the system boundary, or how to model the carbon cycle of biomass.

Environmental LCA evaluations are increasingly relevant for marketing strategies, managing supply chains, and politic decision-making. A higher level of transparency and a harmonisation of the preparation of biogas LCAs are needed to improve the comparability of LCA study results. There is a need to promote the development of common guidelines specific for biogas systems to assess and communicate their environmental performance.

The outcomes of the four evaluated case studies highlight that the best environmental results are obtained with plants fed with agricultural waste instead of energy crops. Covering the digestate storage as well as fully exploiting the surplus heat are effective mitigation solutions. Finally, the capital goods related to the AD plants should be included in the system boundary in particular for small AD plant where their impact is high.

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Author contributions

All the authors conceived the work, JB and CS reviewed the LCA studies; JB collected, processed the data regarding the case studies, JB, AF and CS wrote the paper.

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TABLE

Table 1 - Main review results

Study	Country	Type of LCA study	Numb of Plants	Plant Size	FU	System boundary	Capital good		LUC	Type of ~~Foreground~~ foreground LCI data	~~Digestate~~Multifunctionality issue	Impact (LCIA method)
						Boundary~~System boundary~~	At field level	At field level				
Adelt et al. (2011) [26]	Germany	A	1	n/a	1 m^3 of BMT	cradle to AD plant gate	Included	Included	No	Secondary	n/a	GWP (IPCC 2007), CED
Bacenetti and Fiala (2014) [27]	Italy	A	1	100 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	~~Used~~ Digestate used to fertilize energy crops	GWP, OD, POF, AP, TE, FE, ME, MFRD (ILCD, 2011)
Bacenetti and Fiala (2015) [28]	Italy	A	5	100-999 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary and secondary	Digestate used ~~Used~~ to fertilize energy crops	GWP (IPCC 2007)
Bacenetti et al. (2013) [29]	Italy	A	3	250-999 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate used ~~Used~~ to fertilize energy crops	GWP (IPCC 2007)
Bacenetti et al. (2016) [30]	Italy	A	1	300 kWe	1 kg of milk	cradle to AD plant gate (only AD of slurry)	Included	Included	No	Secondary	Digestate used ~~Used~~ to fertilize fodder crops	GWP, AP, EP (CML2001), CED
Bacenetti et al. (2015) [31]	Italy	A	1	300 kWe	1 kg of tomato puree	cradle to AD plant gate (only AD of slurry)	Secondary	Secondary	No	Secondary	Digestate used ~~Used~~ to fertilize tomato	GWP, OD, POF, AP, TE, FE, ME, MFRD (ILCD, 2011)
Blengini et al., 2011 [32]	Italy	A	n/a	n/a	1 MJ of delivered net heat or EE	cradle to AD plant gate	Included	Included	No	Secondary	~~Replace~~ Digestate replace min. fertilizer	6 (CML 2001)
Borjesson at al. 2015 [33]	Sweden	C	1	170 TJ year-1 in BTM	1 GJ of BMT	cradle to AD plant gate	Included	Included	dLUC	Primary and secondary	~~Replace~~ Digestate replace min. fertilizer	GWP (IPCC 2007)
Borjesson et Berglund. 2007 [34]	Sweden	C	6	n/a	1 MJ heat; heat and EE; kinetic energy	crandle to grave	Included	Included	No	Primary and secondary	Digestate r~~R~~eplace min. fertilizer	GWP; AP; POCP; EP

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Boulamanti et al., 2013 [35]	EU	A	n/a	n/a	1 MJ of EE	cradle to grave	Included	Included	No	Secondary	Digestate ~~Used~~ used to fertilize energy crops	GWP, OD, AP, ADP (CML2001) PM (IMPACT 2002) POF, FE, ME (Recipe), HT (UseTox)
Buratti et al. (2013) [36]	Italy	A	1	1 MWe	1 MJ of BMT	cradle to AD plant gate	Excluded	Excluded	No	Primary	n/a	GWP (IPCC 2007)
Capponi et al (2012) [37]	Italy	A	1	1 MWe	1 kWh of EE	cradle to gate	Excluded	Excluded	No	Primary	Digestate r~~R~~eplace min. fertilizer	GWP (IPCC 2007)
Chen et al. (2012) [38]	China	A	1	$8m^3$	1 MJ produced from biogas combustion	from cradle to grave	Included	Included	No	Secondary	Digestate u~~U~~sed as feed additive & as fertilizer	11 (CML 2001)
Chevalier & Meunier, 2005 [39]	Austria	A	1	86 kWe 148 kWt	1 MJ of EE and 1.6 MJ of heat	crandle to grave	Excluded	Excluded	No	Primary and secondary	~~No~~Digestate not considered	GWP; AP; RDP; EP (EcoIndicator 99)
Cornejo and Wilkie (2010) [40]	Equador	A	n/a	n/a	cattle livestock in 1 year	n/a	Excluded	Excluded	No	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP (IPCC 2007)
Croxatto-Vega et al., 2014 [41]	Denmark	A	n/a	n/a	1 ton of pig slurry	cradle to AD plant gate	Included	Included	No	Secondary	Digestate r~~R~~eplace min. N. fertilizer	18 (Recipe)
De Meester et al., 2012 [42]	NW EU (Germany, Belgium)	A	2	250 - 675 kWe	1 MJ of EE	cradle to grave	Included	Included	No	Primary	n/a	GWP, OD, POF, TE, FE, ME (ILCD)
de Vries et al. (2010) [43]	Western EU		n/a	n/a	1 ton of feedstock (wet)	cradle to grave	Included	Included	No	Secondary	Digestate u~~U~~sed to fertilize energy crops	GWP, AP, EP, CED and LU (Not specified)
de Vries et al. (2012) [44]	Holland	C	1	500 kWe	1 ton of feedstock (wet)	cradle to grave	Included	Included	Yes	Secondary	Digestate r~~R~~eplace min. fertilizer	7 (Recipe)
Dressler et al. (2012) [45]	Germany	A	1	510 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Secondary	Digestate u~~U~~sed to fertilize energy crops	GWP, AP, EP (CML 2001)
Ebner et al. (2015) [46]	USA	A	1	n/a	1 ton of feedstock (wet)	cradle to AD plant gate	n/a	n/a	No	Secondary	n/a	GWP (IPCC 2007)

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Fantin et al, 2015 [47]	Italy	A	1	998 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	primary	Digestate u~~U~~sed to fertilize energy crops	GWP, OD, POF, AC, FE, ME, MFRD. (ILCD 2011)
Fuchsz and Kohlheb (2015) [48]	Germany	A	3	600 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary only for AD plant construction		GWP, AP, EP (not specified)
Fusi et al. 2016 [16]	Italy	A	5	100-999 kWe	1 kWh of EE	cradle to grave	Included	Included	No	Primary	Digestate u~~U~~sed to fertilize energy crops	11 (CML 2001)
Gerin et al., 2008 [49]	Belgium	A	n/a	n/a	1 MWh or EE	cradle to AD plant gate	Excluded	Excluded	No	Secondary	n/a	GWP (IPCC 2007)
Gutierrez et al., (2016) [50]	Cuba	A	n/a	n/a	1 pig (120 kg)	gate to gate (only AD)	Included	Included	No	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EP, ADF, HT, POF (CML 2001)
Hahn at al., (2015) [51]	Germany	A	4	n/a	1 MJ biogas	crandle to grave (EE gen. excluded)	Excluded	Excluded	No	Secondary	~~No~~Digestate not considered	Primary energy; GWP, AP; EP (not specified)
Hamelin et al., (2014) [52]	Denmark	C	n/a	n/a	1 ton of pig slurry	cradle to AD plant gate	Included	Included	iLUC	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EU (EDIP)
Hamelin et al., (2011) [53]	Denmark	C	n/a	n/a	1 ton of pig and cow slurry	cradle to AD plant gate	Included	Included	No	Secondary	Digestate r~~R~~eplace N fertilizer (MFE 75% - 85%) P&K only if needed	GWP, AP, EP (EDIP); PM (Impact 2002+)
Hennig and Gawor, (2012) [54]	Germany	A	4	190 -600 kWe	1 kWh of EE	crandle to grave	Excluded	Excluded	No	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP (IPCC 2007); AP EP (not specified);CED
Ingrao et al. (2015) [55]	Italy	A	1	999 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate r~~U~~sed to fertilize energy crops	GWP (IPCC 2007)
Jin et al. (2015) [2]	China	A	1	n/a	1 ton of food waste	cradle to AD plant gate	Excluded	Excluded	No	Secondary	~~No~~Digestate not considered	GWP, AP. EP, HT, FAETP (CML2001)
Jury et al. (2010) [56]	Luxemburg	A	n/a	n/a	1 MJ of biomethane	cradle to AD plant gate	Included	Included	No	Secondary	Digestate u~~U~~sed to fertilize energy crops	GWP (IPCC 2007) and CED

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Kral et al. (2015) [21]	Austria	A	1	500 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	no	Primary	Digestate u~~U~~se on energy crops or to replace min. fert	GWP (IPCC 2007) FE; (USEtox method)
Kimming et al., (2011) [57]	Sweden	C	1	100 kWe	1 year supply of heat and EE to 150 households	crandle to grave	not speficied	not speficied	No	Secondary	~~No~~Digestate not considered	GWP (IPCC 2007), AP, LU, FER, PER (not specified)
Lansche and Müller, (2011) [58]	Germany	A	1	186 kWe	1 MJ of biogas	cradle to AD plant gate	Included	Included	No	Primary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EP (CML 2001)
Lansche and Müller, 2012 [59]	Germany	A	1	186 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EP (CML 2001)
Lijo et al. (2014~~a~~) [60]	Italy	A	2	250 - 500 kWe	1 ton of feedstock (wet)	cradle to AD plant gate	Included	Included	No	Primary only for AD plant	Digestate r~~Replace~~ min. fertilizer	8 (ReCiPe mid-point)
Lijo et al. (2014~~b~~) [61]	Italy	A	1	500 kWe	100 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary only for AD plant	Digestate r~~R~~eplace min. fertilizer	8 (CML mid-point)
Lijo et al. (2015) [62]	Italy	A	1	1 MWe	1 ton of feedstock (wet)	cradle to AD plant gate	Included	Included	No	Primary only for AD plant	Digestate r~~R~~eplace min. fertilizer	8 (ReCiPe mid-point)
Manninen et al., 2013 [63]	Finland	A	1	85 TJ/year BMT	1 MJ of BMT	cradle to AD plant gate	Excluded	Excluded	No	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP (IPCC 2007) - RED
Meyer-Aurich et al. (2012) [64]	Germany	A	1	500 kWe	1 kWh of EE	cradle to grave	Included	Included	Si	Secondary	Digestate u~~U~~sed to fertilize energy crops	GWP (IPCC 2007)
Mezzullo et al. (2013) [65]	UK	C	1	n/a	1 m^3 of BMT	cradle to grave	Included	Included	No	Secondary	n/a	11 (Ecoindicator 99)
Morero et al. (2015) [66]	Argentina	A	2	531 – 573 kWe	1 m^3 of biogas, 1 kWh of EE	gate to gate: only upgrading	n/a	n/a	No	Primary and secondary	n/a	11 (CML 2001)
Nzila et al. (2012) [67]	Kenya	A	3	16 m^3	1 m^3 of biogas	cradle to grave	Included	Included	No	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP , FD, EC (not specified)
Pacetti et al. (2015) [68]	Italy	A	1	n/a	1 GJ of energy in the biogas	cradle to AD plant gate	Included	Included	No	Secondary	n/a	18 (ReCiPe mid-point)

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Patterson et al., (2011) [4]	Wales	A			275,900 tonnes/yr	cradle to grave	Included	Included	No	Secondary	n/a	Ecoindicator 99 H/A & CML 2001
Pehnt (2006) [69]	Germany	A	1	n/a	1 kWh of EE	cradle to AD plant gate	not speficied	not speficied	No	Secondary	n/a	GWP, CED, AP, EP (not specified)
Pertl et al., (2010) [70]	Austria	A	1	3 MW (biogas capacity)	100 m^3 upgraded biogas	cradle to AD plant gate	Included	Included	No	Secondary	n/a	GWP (IPCC 2007)
Poeschl et al. (2012) [71]	Germany	A	2	< 500 & > 500 kWe	1 ton of feedstock mix	cradle to AD plant gate	Included	Included	No	Secondary	Digestate r~~R~~eplace min. fertilizer	18 (ReCiPe mid-point); 3 (ReCiPe end-point)
Pucker et al. (2013) [72]	Austria	C	6	63 - 1000 kWe; 420.000 Nm^3 BMT	1 MWh of useful energy (heat and EE)	cradle to grave	not speficied	not speficied	No	Primary	No	GWP (IPCC 2007)
Rana et al. (2016) [73]	Italy	A	1	999 kWe	1 MJ of EE	cradle to AD plant gate	Excluded	Excluded	No	Primary	n/a	GWP (RED directive)
Ravina and Genon (2015) [74]	Italy	A	1	1 MWe	1 ton of biogas	cradle to grave	Excluded	Excluded	No	Secondary	No	GWP (IPCC 2007)
Rehl et al., (2012) [75]	Germany	A & C	1	186 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	Secondary	Digestate r~~Allocation &~~ ~~r~~eplace min. fertilizer	11 (CML 2001)
Rivas- Garcia et al., (2015) [76]	Mexico	A	1	n/a	1 kg of milk	cradle to AD plant gate	Included	Included	No	Secondary	Digestate r~~R~~eplace min. fertilizer	18 (Recipe)
Rodriguez-Verde et al. (2014) [77]	Spain	A	1	500 kWe	110,000 t/y of pig slurry	gate to gate (only AD)	Included	Included	No	Primary and secondary	n/a	GWP, OD, ADP, AP, EP, POF (CML 2001)
Schumacher et al. (2010) [78]	Austria	A	1	n/a	1 ha & 1 year	cradle to AD plant gate	Excluded	Excluded	No	Primary and secondary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EP (CML 2001)
Seigl et al., (2011) [79]	Austria	A	30	> 50 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate r~~R~~eplace min. fertilizer	11 (CML 2001)
Siegl at al., (2012) [80]	Austria	C	5	> 50 kWe <500 kWe	1 kWh of EE	crandle to grave	Included	Included	Yes	Primary and secondary	Digestate r~~R~~eplace min. fertilizer	11 (CML 2001)

Styles et al. (2014) [81]	UK	C	4	72-185 kWe	1 year of farm operation	cradle to grave	Included	Included	Yes	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EP and RDP
Styles et al. (2016) [82]	UK	C	n/a	n/a	1 ton of feedstock dry matter	cradle to grave	Included	Included	Yes	Primary and secondary	Digestate r~~R~~eplace min. fertilizer	GWP, AP, EP and RDP (CML 2010)
Tufvesson et al., (2013) [83]	Sweden	A	n/a	n/a	1 MJ of BMT	cradle to AD plant gate	Excluded	Excluded	Yes	Secondary	Digestate r~~R~~eplace min. fertilizer	GWP, EP, AP
Van Stappen et al. (2016) [84]	Belgium	C	1	104 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	Primary and secondary	Digestate r~~R~~eplace min. fertilizer	GWP (IPCC, 2013), HT and Fex (Usetox); EU and TA (CML2001), POF (Recipe); MFRD (ILCD)
Vu et al., 2015 [85]	Vietnam	A	1	n/a	0.1 t of pig manure & 1 t of pig slurry	cradle to AD plant gate	Included	Included	No	Secondaty	Digestate r~~R~~eplace min. fertilizer	GWP, ME, FE, FD (Recipe)
Wang et al (2016) [86]	China	A	n/a	n/a	1 t of pre-dried straw	cradle to gate	Included	Included	No	Primary	n/a	carcinogens, respiratory organics & inorganic, GWP, radiation, OD, Ecotox, AP, EP, LU, minerals and fossil fuels (Eco-indicator 99)
Whiting and Azapagic (2014) [17]	UK	A	1	170 kWe	Co-generation of 1 MWh of heat and EE	cradle to grave	Included	Included	No	Primary and secondary	Digestate r~~R~~eplace min. fertilizers	11 (CML 2001)
Wulf et al., (2006) [87]	Germany	A	n/a	n/a	1 t of OFMSW	cradle to AD plant gate	Excluded	Excluded	No	Secondary	Digestate r~~R~~eplace min. fertilizer (100% ~~per~~ for P-K and NH_4)	GWP (IPCC 2007)
Xu et al. (2015) [88]	China	A	n/a	n/a	1 t of volatile solids	cradle to AD plant gate	Excluded	Excluded	No	Secondary	n/a	18 (ReCiPe)
Zhang et al. (2015) [89]	Canada	A	n/a	n/a	1100 t of dairy slurry	cradle to AD plant gate	Excluded	Excluded	No	Primary and secondary	n/a	7 (CML 2001)

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Zhang et al. (2013) [90]	China	A	1	n/a	Digester volume 8 m^3	cradle to AD plant gate	Included	Included	No	Secondary	n/a	GWP (IPCC 2007)

Note: Type of LCA study: A = attributional, C = consequential; FU = Functional Unit; Capital goods: at field level = tractors, operative machines, farm infrastructures; at AD plant level = digester, CHP engine; LUC = land use change; Impact categories: GWP = global warming potential, CED = cumulative energy demand; FER = Fossil Energy Req., PER = Primary Energy Req. , EC = energy consumption; OD= ozone depletion, POF = Photochemical oxidant formation; AP = acidification potential; EP = eutrophication potential; TE = terrestrial eutrophication, FE = freshwater eutrophication, ME = marine eutrophication, MFRD = mineral fossil resource depletion; FD = fossil depletion; MD = mineral depletion; RDP = resource depletion potential, LU = land use; FAETP = freshwater ecotoxixity, FEx = freshwater ecotoxicity; HT = human toxicity; Impact assessment methodology: CML 2001: [91] Guinée et al, 2002-; Recipe 2008: Goedkoop et al., 2009 [92]; Eco- indicator 99 = Goedkoop and Spriensma, 2001[93]; EDIP: Wenzel et al., 1997 [94]; USEtox method: Rosenbaum et al., 2008 [95]; Impact 2002+: Jolliet et al., 2003 [96]; ILCD 2011: Wolf et al., 2011[97].

Table 2 – Cultivation practice and main input data for maize (MS) and triticale (TS) silage production.

OPERATION	MS		TS	TRACTOR		IMPLEMENT			FC[C] (kg/ha)	EFC[D] (ha/h)	Additional information
	SC[A]	DC[B]	-	Mass (kg)	Power (kW)	Type	Size	Mass (kg)			
Organic fertilization	1	1	1	5050	90	Slurry tank	20 m^3	2000	44 for MS 30 for TS	0.2 for MS 0.3 for TS	80 t/ha digestate for MS 50 t/ha digestate for TS
Ploughing	1	1	1	10500	190	Plough	-	2000	28.5	0.9	
Harrowing	1	1	1	7300	130	Rotary harrow	4.0 m	1800	20.9	0.8	
Sowing	1	1	1	5050	90	Seeder	4 lines	900	44 for MS 30 for TS	0.2 for MS 0.3 for TS	20 kg/ha of seed with pneumatic seeder for MS 170 kg/ha of seed with line seeder for TS
Chemical weed control	2	2		4450	80	Sprayer	15 m	600	3.5 for MS	0.3 for MS	2 times (nicosulfuron 0.5 l/ha, fluroxipir 1 l/ha) + deltametrina 1,5 l/ha for MS
Irrigation	5	4		4450	80	Pump	950 m^3/h	550	10.1 for MS	0.8 for MS	5200 m^3/ha for MS SC; 4400 m^3/ha for MS DC
Mechanical weed Control	1	1		5050	90	Hoeing	2.8 m	550	3.1 for MS	2.5 for MS	
Top fertilization	1	1		6850	120	Spreader	2500 dm^3	500	2.8 for MS	5.5 for MS	60 kg/ha urea from MS
Harvest	1	1	1	-		Forage harvester	335 kW	13000	39.0 for MS 29.6 for TS	1.5 for MS 2.0 for TS	MS yield: 66, 68, 49.5 and 55.1 t/ha for plant A, B, C and D, respectively; TS yield: 34.5, 36, 34.5 for plant A, C and D, respectively
Transport	1	1	1	5050	90	Farm trailers	30 m^3	5500	10.1	0.5	3 farm trailers for MS, 2 for TS
Ensilage	1	1	1	5050	90	2 Frontal loaders	2 m^3	450	0.44[E]	0.5	In bunker silos

[A] = single crop cropping system, [B] = double crop cropping system; [C] = fuel consumption; [D] = effective field capacity; [E] = kg/t (Bacenetti and Fusi, 2015).

Table 3 - Main LCI data for the four agricultural AD plants

Parameter	Unit	AD plant			
		1	2	3	4
Temperature	°C	39-40	39-40	39-40	39-40
CHP electrical power	kW	999	999	485	220
Thermal power	kW	1100	1100	588	300
Electric efficiency	%	40.8	40.8	39.5	37.0
Thermal efficiency	%	45	45	48	50
Working time	h/year	7995	8230	8050	8210
Electricity production	MWh/year	7994	8216	3895	1825
Heat production	MWh/year	8817	9062	4733	2467
Digesters	-	2	2	1	1
Digester Volume	m^3	2750	2750	2500	2000
Post digesters	-	2	2	2	1
Post digester Volume	m^3	3000	3200	3000	2250
Specific volume	m^3/kW	11.5	11.9	17.6	19.1
Electricity consumption	MWh/year	699.48	739.47	319.38	171.57
Heat consumption	MWh/year	1459	2216	1592	1561
Maize silage	t/day	45	45	10	0
Triticale silage	t/day	10	0	10	0
Pig slurry	t/day	0	0	50	50
Cattle slurry	t/day	0	72	70	75
Water	t/day	0	10	0	0
Liquid fraction	t/day	130	100	0	0
Lubricating oil	kg/year	2158.4	2218.4	1051.6	492.8
NaOH	kg/year	471.6	484.8	229.8	107.7
Methane losses	kg/year	27429	28191	13804	6906

Table 4 - Impact variation (%) related to covering of digestate tank.

Impact category	A	B	C	D
GWP	-47.8%	-127.4%	-72.6%	-18.2%
OD	-17.4%	-19.8%	-18.6%	-24.2%
HTc	-1.0%	-1.1%	+4.5%	+10.1%
HTnoc	-0.1%	-0.1%	+0.3%	+0.8%
PM	-10.1%	-11.9%	-12.1%	-33.0%
POF	-15.9%	-23.1%	-40.4%	-26.8%
TA	-9.9%	-11.7%	-13.5%	-56.8%
TE	-8.9%	-10.6%	-12.4%	-63.2%
FE	0.0%	0.1%	0.2%	13.1%
ME	-4.3%	-9.6%	-4.6%	-25.7%
FEx	-0.1%	-0.1%	+0.1%	+4.4%
MFRD	+11.2%	+13.2%	+24.1%	+69.7%

Table 5 - Impact variation (%) ~~arising from~~due to surplus heat valorisation (Marginal technology: heat production in domestic boiler fed with natural gas).

Impact category	Δ of impact related to different exploitation share of surplus heat											
	Plant A			Plant B			Plant C			Plant D		
	100%	**50%**	**25%**	**100%**	**50%**	**25%**	**100%**	**50%**	**25%**	**100%**	**50%**	**25%**
GWP	-46.1%	-23.4%	-12.0%	-111%	-56.4%	-29.0%	-62.1%	-31.6%	-16.4%	-9.6%	-5.0%	-2.7%
OD	-333%	-168%	-85.1%	-344%	-173%	-88.0%	-339%	-171%	-87.6%	-301%	-154%	-80.3%
HTc	-54.8%	-34.0%	-23.6%	-55.3%	-34.7%	-24.4%	-52.8%	-34.9%	-26.0%	-48.8%	-35.5%	-28.8%
HTnoc	-4.6%	-3.0%	-2.1%	-4.6%	-2.9%	-2.1%	-4.6%	-3.1%	-2.4%	-4.0%	-3.0%	-2.5%
PM	-7.6%	-4.1%	-2.4%	-8.1%	-4.4%	-2.6%	-9.2%	-5.1%	-3.1%	-19.0%	-11.5%	-7.7%
POF	-33.2%	-17.0%	-9.0%	-43.9%	-22.6%	-11.9%	-79.7%	-41.4%	-22.2%	-35.6%	-19.1%	-10.9%
TA	-4.1%	-2.2%	-1.2%	-4.4%	-2.3%	-1.3%	-5.1%	-2.8%	-1.6%	-14.2%	-8.1%	-5.1%
TE	-2.2%	-1.1%	-0.6%	-2.4%	-1.2%	-0.7%	-2.7%	-1.4%	-0.8%	-8.9%	-4.9%	-2.9%
FE	-1.1%	-0.6%	-0.4%	-1.7%	-1.0%	-0.6%	-1.3%	-0.8%	-0.6%	-44.3%	-30.4%	-23.4%
ME	-7.4%	-3.8%	-2.0%	-15.2%	-7.9%	-4.2%	-7.6%	-4.0%	-2.2%	-29.1%	-15.9%	-9.3%
FEx	-1.2%	-0.8%	-0.5%	-1.2%	-0.7%	-0.5%	-1.9%	-1.3%	-1.0%	-27.3%	-20.0%	-16.3%
MFRD	-24.4%	-13.4%	-8.0%	-26.4%	-14.6%	-8.8%	-25.9%	-14.8%	-9.3%	-35.2%	-22.0%	-15.4%

Table 6 - Impact variation (%) related to the exclusion of infrastructures of the AD plant (digesters and CHP engine) from the system boundary.

Impact category	Plant			
	A	**B**	**C**	**D**
GWP	-1.38%	-3.60%	-2.91%	-0.93%
OD	-5.49%	-6.10%	-8.60%	-15.81%
HTc	-33.90%	-36.27%	-46.61%	-66.04%
HTnoc	-3.02%	-3.13%	-4.11%	-5.11%
PM	-1.70%	-1.96%	-3.20%	-12.18%
POF	-2.22%	-3.16%	-8.40%	-7.54%
TA	-0.52%	-0.60%	-0.98%	-5.10%
TE	-0.20%	-0.23%	-0.39%	-2.54%
FE	-0.50%	-0.83%	-0.93%	-52.45%
ME	-0.64%	-1.42%	-1.04%	-7.96%
FEx	-0.77%	-0.78%	-1.70%	-36.96%
MFRD	-5.37%	-6.22%	-8.34%	-19.85%

TABLE

Table 1 - Main review results

Study	Country	Type of LCA study	Numb of Plants	Plant Size	FU	System boundary				Type of foreground LCI data	Multifunctionality issue	Impact (LCIA method)
						Boundary	Capital good		LUC			
							At field level	At field level				
Adelt et al. (2011) [26]	Germany	A	1	n/a	1 m^3 of BMT	cradle to AD plant gate	Included	Included	No	Secondary	n/a	GWP (IPCC 2007), CED
Bacenetti and Fiala (2014) [27]	Italy	A	1	100 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate used to fertilize energy crops	GWP, OD, POF, AP, TE, FE, ME, MFRD (ILCD, 2011)
Bacenetti and Fiala (2015) [28]	Italy	A	5	100-999 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary and secondary	Digestate used to fertilize energy crops	GWP (IPCC 2007)
Bacenetti et al. (2013) [29]	Italy	A	3	250-999 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate used to fertilize energy crops	GWP (IPCC 2007)
Bacenetti et al. (2016) [30]	Italy	A	1	300 kWe	1 kg of milk	cradle to AD plant gate (only AD of slurry)	Included	Included	No	Secondary	Digestate used to fertilize fodder crops	GWP, AP, EP (CML2001), CED
Bacenetti et al. (2015) [31]	Italy	A	1	300 kWe	1 kg of tomato puree	cradle to AD plant gate (only AD of slurry)	Secondary	Secondary	No	Secondary	Digestate used to fertilize tomato	GWP, OD, POF, AP, TE, FE, ME, MFRD (ILCD, 2011)
Blengini et al., 2011 [32]	Italy	A	n/a	n/a	1 MJ of delivered net heat or EE	cradle to AD plant gate	Included	Included	No	Secondary	Digestate replace min. fertilizer	6 (CML 2001)
Borjesson at al. 2015 [33]	Sweden	C	1	170 TJ year-1 in BTM	1 GJ of BMT	cradle to AD plant gate	Included	Included	dLUC	Primary and secondary	Digestate replace min. fertilizer	GWP (IPCC 2007)
Borjesson et Berglund. 2007 [34]	Sweden	C	6	n/a	1 MJ heat; heat and EE; kinetic energy	crandle to grave	Included	Included	No	Primary and secondary	Digestate replace min. fertilizer	GWP; AP; POCP; EP

Boulamanti et al., 2013 [35]	EU	A	n/a	n/a	1 MJ of EE	cradle to grave	Included	Included	No	Secondary	Digestate used to fertilize energy crops	GWP, OD, AP, ADP (CML2001) PM (IMPACT 2002) POF, FE, ME (Recipe), HT (UseTox)
Buratti et al. (2013) [36]	Italy	A	1	1 MWe	1 MJ of BMT	cradle to AD plant gate	Excluded	Excluded	No	Primary	n/a	GWP (IPCC 2007)
Capponi et al (2012) [37]	Italy	A	1	1 MWe	1 kWh of EE	cradle to gate	Excluded	Excluded	No	Primary	Digestate replace min. fertilizer	GWP (IPCC 2007)
Chen et al. (2012) [38]	China	A	1	$8m^3$	1 MJ produced from biogas combustion	from cradle to grave	Included	Included	No	Secondary	Digestate used as feed additive & as fertilizer	11 (CML 2001)
Chevalier & Meunier, 2005 [39]	Austria	A	1	86 kWe 148 kWt	1 MJ of EE and 1.6 MJ of heat	crandle to grave	Excluded	Excluded	No	Primary and secondary	Digestate not considered	GWP; AP; RDP; EP (EcoIndicator 99)
Cornejo and Wilkie (2010) [40]	Equador	A	n/a	n/a	cattle livestock in 1 year	n/a	Excluded	Excluded	No	Secondary	Digestate replace min. fertilizer	GWP (IPCC 2007)
Croxatto-Vega et al., 2014 [41]	Denmark	A	n/a	n/a	1 ton of pig slurry	cradle to AD plant gate	Included	Included	No	Secondary	Digestate replace min. N. fertilizer	18 (Recipe)
De Meester et al., 2012 [42]	NW EU (Germany, Belgium)	A	2	250 - 675 kWe	1 MJ of EE	cradle to grave	Included	Included	No	Primary	n/a	GWP, OD, POF, TE, FE, ME (ILCD)
de Vries et al. (2010) [43]	Western EU		n/a	n/a	1 ton of feedstock (wet)	cradle to grave	Included	Included	No	Secondary	Digestate used to fertilize energy crops	GWP, AP, EP, CED and LU (Not specified)
de Vries et al. (2012) [44]	Holland	C	1	500 kWe	1 ton of feedstock (wet)	cradle to grave	Included	Included	Yes	Secondary	Digestate replace min. fertilizer	7 (Recipe)
Dressler et al. (2012) [45]	Germany	A	1	510 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Secondary	Digestate used to fertilize energy crops	GWP, AP, EP (CML 2001)
Ebner et al. (2015) [46]	USA	A	1	n/a	1 ton of feedstock (wet)	cradle to AD plant gate	n/a	n/a	No	Secondary	n/a	GWP (IPCC 2007)

Fantin et al, 2015 [47]	Italy	A	1	998 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	primary	Digestate used to fertilize energy crops	GWP, OD, POF, AC, FE, ME, MFRD. (ILCD 2011)
Fuchsz and Kohlheb (2015) [48]	Germany	A	3	600 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary only for AD plant construction		GWP, AP, EP (not specified)
Fusi et al. 2016 [16]	Italy	A	5	100-999 kWe	1 kWh of EE	cradle to grave	Included	Included	No	Primary	Digestate used to fertilize energy crops	11 (CML 2001)
Gerin et al., 2008 [49]	Belgium	A	n/a	n/a	1 MWh or EE	cradle to AD plant gate	Excluded	Excluded	No	Secondary	n/a	GWP (IPCC 2007)
Gutierrez et al., (2016) [50]	Cuba	A	n/a	n/a	1 pig (120 kg)	gate to gate (only AD)	Included	Included	No	Secondary	Digestate replace min. fertilizer	GWP, AP, EP, ADF, HT, POF (CML 2001)
Hahn at al., (2015) [51]	Germany	A	4	n/a	1 MJ biogas	crandle to grave (EE gen. excluded)	Excluded	Excluded	No	Secondary	Digestate not considered	Primary energy; GWP, AP; EP (not specified)
Hamelin et al., (2014) [52]	Denmark	C	n/a	n/a	1 ton of pig slurry	cradle to AD plant gate	Included	Included	iLUC	Secondary	Digestate replace min. fertilizer	GWP, AP, EU (EDIP)
Hamelin et al., (2011) [53]	Denmark	C	n/a	n/a	1 ton of pig and cow slurry	cradle to AD plant gate	Included	Included	No	Secondary	Digestate replace N fertilizer (MFE 75% - 85%) P&K only if needed	GWP, AP, EP (EDIP); PM (Impact 2002+)
Hennig and Gawor, (2012) [54]	Germany	A	4	190 -600 kWe	1 kWh of EE	crandle to grave	Excluded	Excluded	No	Secondary	Digestate replace min. fertilizer	GWP (IPCC 2007); AP EP (not specified);CED
Ingrao et al. (2015) [55]	Italy	A	1	999 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate rsed to fertilize energy crops	GWP (IPCC 2007)
Jin et al. (2015) [2]	China	A	1	n/a	1 ton of food waste	cradle to AD plant gate	Excluded	Excluded	No	Secondary	Digestate not considered	GWP, AP. EP, HT, FAETP (CML2001)
Jury et al. (2010) [56]	Luxemburg	A	n/a	n/a	1 MJ of biomethane	cradle to AD plant gate	Included	Included	No	Secondary	Digestate used to fertilize energy crops	GWP (IPCC 2007) and CED

Kral et al. (2015) [21]	Austria	A	1	500 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	no	Primary	Digestate use on energy crops or to replace min. fert	GWP (IPCC 2007) FEx (USEtox method)
Kimming et al., (2011) [57]	Sweden	C	1	100 kWe	1 year supply of heat and EE to 150 households	crandle to grave	not speficied	not speficied	No	Secondary	Digestate not considered	GWP (IPCC 2007), AP, LU, FER, PER (not specified)
Lansche and Müller, (2011) [58]	Germany	A	1	186 kWe	1 MJ of biogas	cradle to AD plant gate	Included	Included	No	Primary	Digestate replace min. fertilizer	GWP, AP, EP (CML 2001)
Lansche and Müller, 2012 [59]	Germany	A	1	186 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate replace min. fertilizer	GWP, AP, EP (CML 2001)
Lijo et al. (2014) [60]	Italy	A	2	250 - 500 kWe	1 ton of feedstock (wet)	cradle to AD plant gate	Included	Included	No	Primary only for AD plant	Digestate rmin. fertilizer	8 (ReCiPe mid-point)
Lijo et al. (2014) [61]	Italy	A	1	500 kWe	100 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary only for AD plant	Digestate replace min. fertilizer	8 (CML mid-point)
Lijo et al. (2015) [62]	Italy	A	1	1 MWe	1 ton of feedstock (wet)	cradle to AD plant gate	Included	Included	No	Primary only for AD plant	Digestate replace min. fertilizer	8 (ReCiPe mid-point)
Manninen et al., 2013 [63]	Finland	A	1	85 TJ/year BMT	1 MJ of BMT	cradle to AD plant gate	Excluded	Excluded	No	Secondary	Digestate replace min. fertilizer	GWP (IPCC 2007) - RED
Meyer-Aurich et al. (2012) [64]	Germany	A	1	500 kWe	1 kWh of EE	cradle to grave	Included	Included	Si	Secondary	Digestate used to fertilize energy crops	GWP (IPCC 2007)
Mezzullo et al. (2013) [65]	UK	C	1	n/a	1 m^3 of BMT	cradle to grave	Included	Included	No	Secondary	n/a	11 (Ecoindicator 99)
Morero et al. (2015) [66]	Argentina	A	2	531 – 573 kWe	1 m^3 of biogas, 1 kWh of EE	gate to gate: only upgrading	n/a	n/a	No	Primary and secondary	n/a	11 (CML 2001)
Nzila et al. (2012) [67]	Kenya	A	3	16 m^3	1 m^3 of biogas	cradle to grave	Included	Included	No	Secondary	Digestate replace min. fertilizer	GWP , FD, EC (not specified)
Pacetti et al. (2015) [68]	Italy	A	1	n/a	1 GJ of energy in the biogas	cradle to AD plant gate	Included	Included	No	Secondary	n/a	18 (ReCiPe mid-point)

Patterson et al., (2011) [4]	Wales	A			275,900 tonnes/yr	cradle to grave	Included	Included	No	Secondary	n/a	Ecoindicator 99 H/A & CML 2001
Pehnt (2006) [69]	Germany	A	1	n/a	1 kWh of EE	cradle to AD plant gate	not speficied	not speficied	No	Secondary	n/a	GWP, CED, AP, EP (not specified)
Pertl et al., (2010) [70]	Austria	A	1	3 MW (biogas capacity)	100 m^3 upgraded biogas	cradle to AD plant gate	Included	Included	No	Secondary	n/a	GWP (IPCC 2007)
Poeschl et al. (2012) [71]	Germany	A	2	< 500 & > 500 kWe	1 ton of feedstock mix	cradle to AD plant gate	Included	Included	No	Secondary	Digestate replace min. fertilizer	18 (ReCiPe mid-point); 3 (ReCiPe end-point)
Pucker et al. (2013) [72]	Austria	C	6	63 - 1000 kWe; 420.000 Nm^3 BMT	1 MWh of useful energy (heat and EE)	cradle to grave	not speficied	not speficied	No	Primary	No	GWP (IPCC 2007)
Rana et al. (2016) [73]	Italy	A	1	999 kWe	1 MJ of EE	cradle to AD plant gate	Excluded	Excluded	No	Primary	n/a	GWP (RED directive)
Ravina and Genon (2015) [74]	Italy	A	1	1 MWe	1 ton of biogas	cradle to grave	Excluded	Excluded	No	Secondary	No	GWP (IPCC 2007)
Rehl et al., (2012) [75]	Germany	A & C	1	186 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	Secondary	Digestate replace min. fertilizer	11 (CML 2001)
Rivas- Garcia et al., (2015) [76]	Mexico	A	1	n/a	1 kg of milk	cradle to AD plant gate	Included	Included	No	Secondary	Digestate replace min. fertilizer	18 (Recipe)
Rodriguez-Verde et al. (2014) [77]	Spain	A	1	500 kWe	110,000 t/y of pig slurry	gate to gate (only AD)	Included	Included	No	Primary and secondary	n/a	GWP, OD, ADP, AP, EP, POF (CML 2001)
Schumacher et al. (2010) [78]	Austria	A	1	n/a	1 ha & 1 year	cradle to AD plant gate	Excluded	Excluded	No	Primary and secondary	Digestate replace min. fertilizer	GWP, AP, EP (CML 2001)
Seigl et al., (2011) [79]	Austria	A	30	> 50 kWe	1 kWh of EE	cradle to AD plant gate	Included	Included	No	Primary	Digestate replace min. fertilizer	11 (CML 2001)
Siegl at al., (2012) [80]	Austria	C	5	> 50 kWe <500 kWe	1 kWh of EE	crandle to grave	Included	Included	Yes	Primary and secondary	Digestate replace min. fertilizer	11 (CML 2001)
Styles et al. (2014) [81]	UK	C	4	72-185 kWe	1 year of farm operation	cradle to grave	Included	Included	Yes	Secondary	Digestate replace min. fertilizer	GWP, AP, EP and RDP

Styles et al. (2016) [82]	UK	C	n/a	n/a	1 ton of feedstock dry matter	cradle to grave	Included	Included	Yes	Primary and secondary	Digestate replace min. fertilizer	GWP, AP, EP and RDP (CML 2010)
Tufvesson et al., (2013) [83]	Sweden	A	n/a	n/a	1 MJ of BMT	cradle to AD plant gate	Excluded	Excluded	Yes	Secondary	Digestate replace min. fertilizer	GWP, EP, AP
Van Stappen et al. (2016) [84]	Belgium	C	1	104 kWe	1 MJ of EE	cradle to AD plant gate	Included	Included	No	Primary and secondary	Digestate replace min. fertilizer	GWP (IPCC, 2013), HT and Fex (Usetox); EU and TA (CML2001), POF (Recipe); MFRD (ILCD)
Vu et al., 2015 [85]	Vietnam	A	1	n/a	0.1 t of pig manure & 1 t of pig slurry	cradle to AD plant gate	Included	Included	No	Secondaty	Digestate replace min. fertilizer	GWP, ME, FE, FD (Recipe)
Wang et al (2016) [86]	China	A	n/a	n/a	1 t of pre-dried straw	cradle to gate	Included	Included	No	Primary	n/a	carcinogens, respiratory organics & inorganic, GWP, radiation, OD, Ecotox, AP, EP, LU, minerals and fossil fuels (Eco-indicator 99)
Whiting and Azapagic (2014) [17]	UK	A	1	170 kWe	Co-generation of 1 MWh of heat and EE	cradle to grave	Included	Included	No	Primary and secondary	Digestate replace min. fertilizers	11 (CML 2001)
Wulf et al., (2006) [87]	Germany	A	n/a	n/a	1 t of OFMSW	cradle to AD plant gate	Excluded	Excluded	No	Secondary	Digestate replace min. fertilizer (100% for P-K and NH_4)	GWP (IPCC 2007)
Xu et al. (2015) [88]	China	A	n/a	n/a	1 t of volatile solids	cradle to AD plant gate	Excluded	Excluded	No	Secondary	n/a	18 (ReCiPe)
Zhang et al. (2015) [89]	Canada	A	n/a	n/a	1100 t of dairy slurry	cradle to AD plant gate	Excluded	Excluded	No	Primary and secondary	n/a	7 (CML 2001)
Zhang et al. (2013) [90]	China	A	1	n/a	Digester volume 8 m^3	cradle to AD plant gate	Included	Included	No	Secondary	n/a	GWP (IPCC 2007)

Note: Type of LCA study: A = attributional, C = consequential; FU = Functional Unit; Capital goods: at field level = tractors, operative machines, farm infrastructures; at AD plant level = digester, CHP engine; LUC = land use change; Impact categories: GWP = global warming potential, CED = cumulative energy demand; FER = Fossil Energy Req., PER = Primary Energy Req. , EC = energy consumption; OD= ozone depletion, POF = Photochemical oxidant formation; AP = acidification potential; EP = eutrophication potential; TE = terrestrial eutrophication, FE = freshwater eutrophication, ME = marine eutrophication, MFRD = mineral fossil resource depletion; FD = fossil depletion; MD = mineral depletion; RDP = resource depletion potential, LU = land use; FAETP = freshwater ecotoxixity, FEx = freshwater ecotoxicity; HT = human toxicity; Impact assessment methodology: CML 2001: [91] Guinée et al, 2002; Recipe 2008: Goedkoop et al., 2009 [92]; Eco- indicator 99 = Goedkoop and Spriensma, 2001[93]; EDIP: Wenzel et al., 1997 [94]; USEtox method: Rosenbaum et al., 2008 [95]; Impact 2002+: Jolliet et al., 2003 [96]; ILCD 2011: Wolf et al., 2011[97].

Table 2 - Cultivation practice and main input data for maize (MS) and triticale (TS) silage production.

OPERATION	MS		TS	TRACTOR		IMPLEMENT			FC[C] (kg/ha)	EFC[D] (ha/h)	Additional information
	SC[A]	DC[B]	-	Mass (kg)	Power (kW)	Type	Size	Mass (kg)			
Organic fertilization	1	1	1	5050	90	Slurry tank	20 m^3	2000	44 for MS 30 for TS	0.2 for MS 0.3 for TS	80 t/ha digestate for MS 50 t/ha digestate for TS
Ploughing	1	1	1	10500	190	Plough	-	2000	28.5	0.9	
Harrowing	1	1	1	7300	130	Rotary harrow	4.0 m	1800	20.9	0.8	
Sowing	1	1	1	5050	90	Seeder	4 lines	900	44 for MS 30 for TS	0.2 for MS 0.3 for TS	20 kg/ha of seed with pneumatic seeder for MS 170 kg/ha of seed with line seeder for TS
Chemical weed control	2	2		4450	80	Sprayer	15 m	600	3.5 for MS	0.3 for MS	2 times (nicosulfuron 0.5 l/ha, fluroxipir 1 l/ha) + deltametrina 1,5 l/ha for MS
Irrigation	5	4		4450	80	Pump	950 m^3/h	550	10.1 for MS	0.8 for MS	5200 m^3/ha for MS SC; 4400 m^3/ha for MS DC
Mechanical weed Control	1	1		5050	90	Hoeing	2.8 m	550	3.1 for MS	2.5 for MS	
Top fertilization	1	1		6850	120	Spreader	2500 dm^3	500	2.8 for MS	5.5 for MS	60 kg/ha urea from MS
Harvest	1	1	1	-		Forage harvester	335 kW	13000	39.0 for MS 29.6 for TS	1.5 for MS 2.0 for TS	MS yield: 66, 68, 49.5 and 55.1 t/ha for plant A, B, C and D, respectively; TS yield: 34.5, 36, 34.5 for plant A, C and D, respectively
Transport	1	1	1	5050	90	Farm trailers	30 m^3	5500	10.1	0.5	3 farm trailers for MS, 2 for TS
Ensilage	1	1	1	5050	90	2 Frontal loaders	2 m^3	450	0.44[E]	0.5	In bunker silos

[A] = single crop cropping system, [B] = double crop cropping system; [C] = fuel consumption; [D] = effective field capacity; [E] = kg/t (Bacenetti and Fusi, 2015).

Table 3 - Main LCI data for the four agricultural AD plants

Parameter	Unit	AD plant			
		1	2	3	4
Temperature	°C	39-40	39-40	39-40	39-40
CHP electrical power	kW	999	999	485	220
Thermal power	kW	1100	1100	588	300
Electric efficiency	%	40.8	40.8	39.5	37.0
Thermal efficiency	%	45	45	48	50
Working time	h/year	7995	8230	8050	8210
Electricity production	MWh/year	7994	8216	3895	1825
Heat production	MWh/year	8817	9062	4733	2467
Digesters	-	2	2	1	1
Digester Volume	m^3	2750	2750	2500	2000
Post digesters	-	2	2	2	1
Post digester Volume	m^3	3000	3200	3000	2250
Specific volume	m^3/kW	11.5	11.9	17.6	19.1
Electricity consumption	MWh/year	699.48	739.47	319.38	171.57
Heat consumption	MWh/year	1459	2216	1592	1561
Maize silage	t/day	45	45	10	0
Triticale silage	t/day	10	0	10	0
Pig slurry	t/day	0	0	50	50
Cattle slurry	t/day	0	72	70	75
Water	t/day	0	10	0	0
Liquid fraction	t/day	130	100	0	0
Lubricating oil	kg/year	2158.4	2218.4	1051.6	492.8
NaOH	kg/year	471.6	484.8	229.8	107.7
Methane losses	kg/year	27429	28191	13804	6906

Table 4 - Impact variation (%) related to covering of digestate tanks.

Impact category	A	B	C	D
GWP	-47.8%	-127.4%	-72.6%	-18.2%
OD	-17.4%	-19.8%	-18.6%	-24.2%
HTc	-1.0%	-1.1%	+4.5%	+10.1%
HTnoc	-0.1%	-0.1%	+0.3%	+0.8%
PM	-10.1%	-11.9%	-12.1%	-33.0%
POF	-15.9%	-23.1%	-40.4%	-26.8%
TA	-9.9%	-11.7%	-13.5%	-56.8%
TE	-8.9%	-10.6%	-12.4%	-63.2%
FE	0.0%	0.1%	0.2%	13.1%
ME	-4.3%	-9.6%	-4.6%	-25.7%
FEx	-0.1%	-0.1%	+0.1%	+4.4%
MFRD	+11.2%	+13.2%	+24.1%	+69.7%

Table 5 - Impact variation (%) due to surplus heat valorisation (Marginal technology: heat production in domestic boiler fed with natural gas).

Impact category	Δ of impact related to different exploitation share of surplus heat											
	Plant A			Plant B			Plant C			Plant D		
	100%	50%	25%	100%	50%	25%	100%	50%	25%	100%	50%	25%
GWP	-46.1%	-23.4%	-12.0%	-111%	-56.4%	-29.0%	-62.1%	-31.6%	-16.4%	-9.6%	-5.0%	-2.7%
OD	-333%	-168%	-85.1%	-344%	-173%	-88.0%	-339%	-171%	-87.6%	-301%	-154%	-80.3%
HTc	-54.8%	-34.0%	-23.6%	-55.3%	-34.7%	-24.4%	-52.8%	-34.9%	-26.0%	-48.8%	-35.5%	-28.8%
HTnoc	-4.6%	-3.0%	-2.1%	-4.6%	-2.9%	-2.1%	-4.6%	-3.1%	-2.4%	-4.0%	-3.0%	-2.5%
PM	-7.6%	-4.1%	-2.4%	-8.1%	-4.4%	-2.6%	-9.2%	-5.1%	-3.1%	-19.0%	-11.5%	-7.7%
POF	-33.2%	-17.0%	-9.0%	-43.9%	-22.6%	-11.9%	-79.7%	-41.4%	-22.2%	-35.6%	-19.1%	-10.9%
TA	-4.1%	-2.2%	-1.2%	-4.4%	-2.3%	-1.3%	-5.1%	-2.8%	-1.6%	-14.2%	-8.1%	-5.1%
TE	-2.2%	-1.1%	-0.6%	-2.4%	-1.2%	-0.7%	-2.7%	-1.4%	-0.8%	-8.9%	-4.9%	-2.9%
FE	-1.1%	-0.6%	-0.4%	-1.7%	-1.0%	-0.6%	-1.3%	-0.8%	-0.6%	-44.3%	-30.4%	-23.4%
ME	-7.4%	-3.8%	-2.0%	-15.2%	-7.9%	-4.2%	-7.6%	-4.0%	-2.2%	-29.1%	-15.9%	-9.3%
FEx	-1.2%	-0.8%	-0.5%	-1.2%	-0.7%	-0.5%	-1.9%	-1.3%	-1.0%	-27.3%	-20.0%	-16.3%
MFRD	-24.4%	-13.4%	-8.0%	-26.4%	-14.6%	-8.8%	-25.9%	-14.8%	-9.3%	-35.2%	-22.0%	-15.4%

Table 6 - Impact variation (%) related to the exclusion of infrastructures of the AD plant (digesters and CHP engine) from the system boundary.

Impact category	Plant			
	A	B	C	D
GWP	-1.38%	-3.60%	-2.91%	-0.93%
OD	-5.49%	-6.10%	-8.60%	-15.81%
HTc	-33.90%	-36.27%	-46.61%	-66.04%
HTnoc	-3.02%	-3.13%	-4.11%	-5.11%
PM	-1.70%	-1.96%	-3.20%	-12.18%
POF	-2.22%	-3.16%	-8.40%	-7.54%
TA	-0.52%	-0.60%	-0.98%	-5.10%
TE	-0.20%	-0.23%	-0.39%	-2.54%
FE	-0.50%	-0.83%	-0.93%	-52.45%
ME	-0.64%	-1.42%	-1.04%	-7.96%
FEx	-0.77%	-0.78%	-1.70%	-36.96%
MFRD	-5.37%	-6.22%	-8.34%	-19.85%

FIGURE CAPTIONS

Figure 1 – Product (in blue) and co-products (in red) stemming from an agricultural AD plants

Figure 2 – Comparison of the GWP results for electricity production among the different LCA studies (the bars represent the minimum and maximum value achieved while the dot the single value)

Figure 3 – System boundary for the 4 AD plants: at the top, plant 1 where only cereal silages are digested; in the middle, plants 2 and 3 where silages are co-digested with animal slurries; at the bottom, plant 4 fed only with animal slurries. (CC: Cereal cultivation; SL = animal slurry; R: digester; T (D): digestate tank; SP: separator (LF, SF); T (LF): liquid fraction tank; S: scrubber; C: chiller; FL: biogas flare; HE: heat exchanger; CHP: engine-generator; ICE: internal combustion engine)

Figure 4 - Environmental impact results for 1 kWh of produced electricity

Figure 1

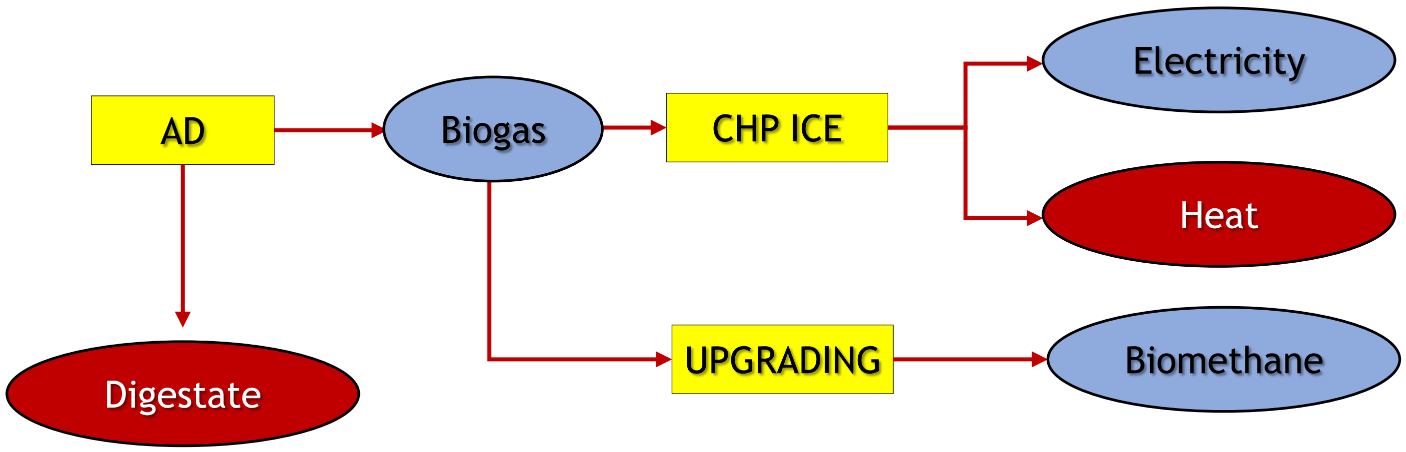
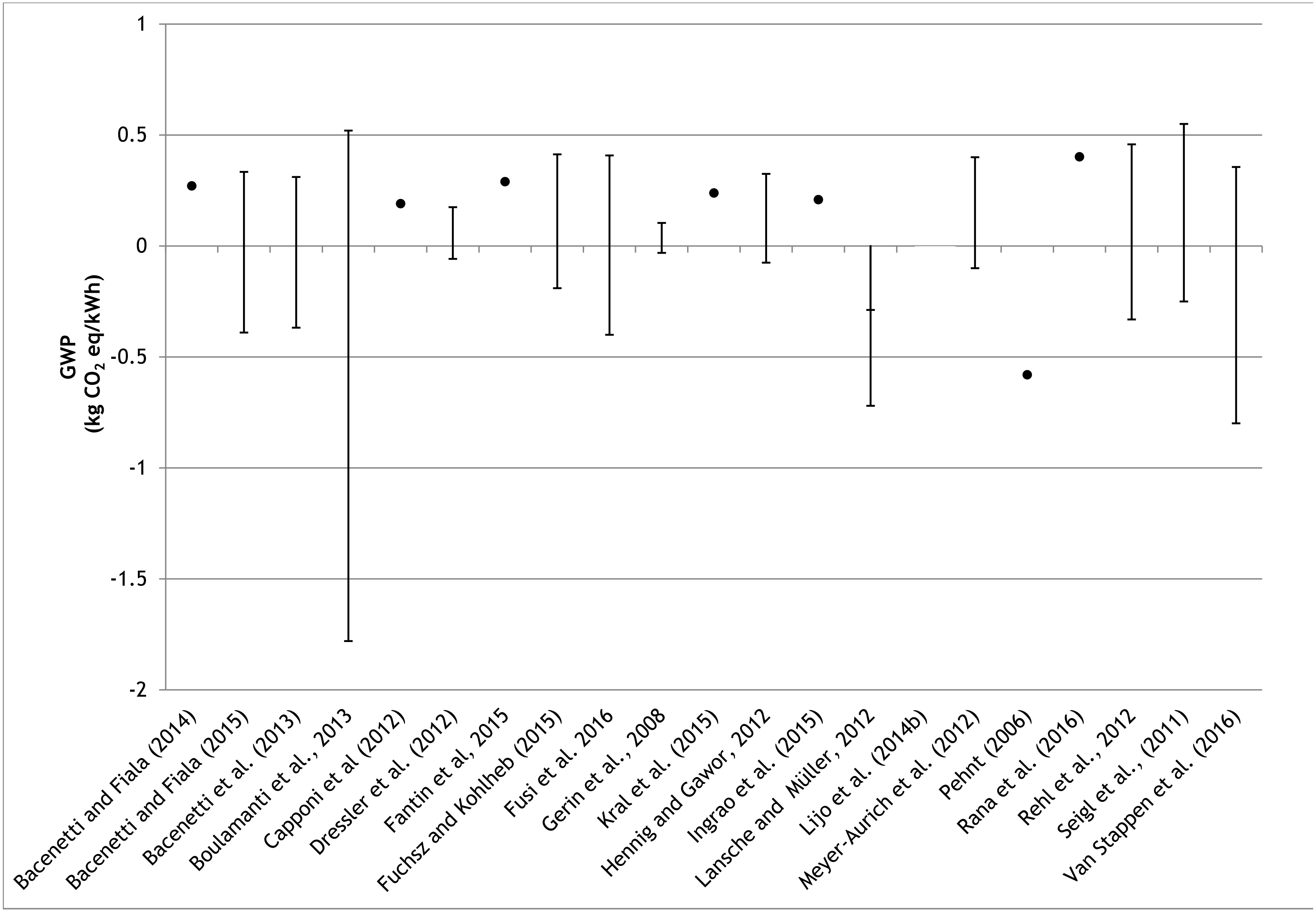

AD
Biogas
CHP ICE
Electricity
Heat
Digestate
UPGRADING
Biomethane

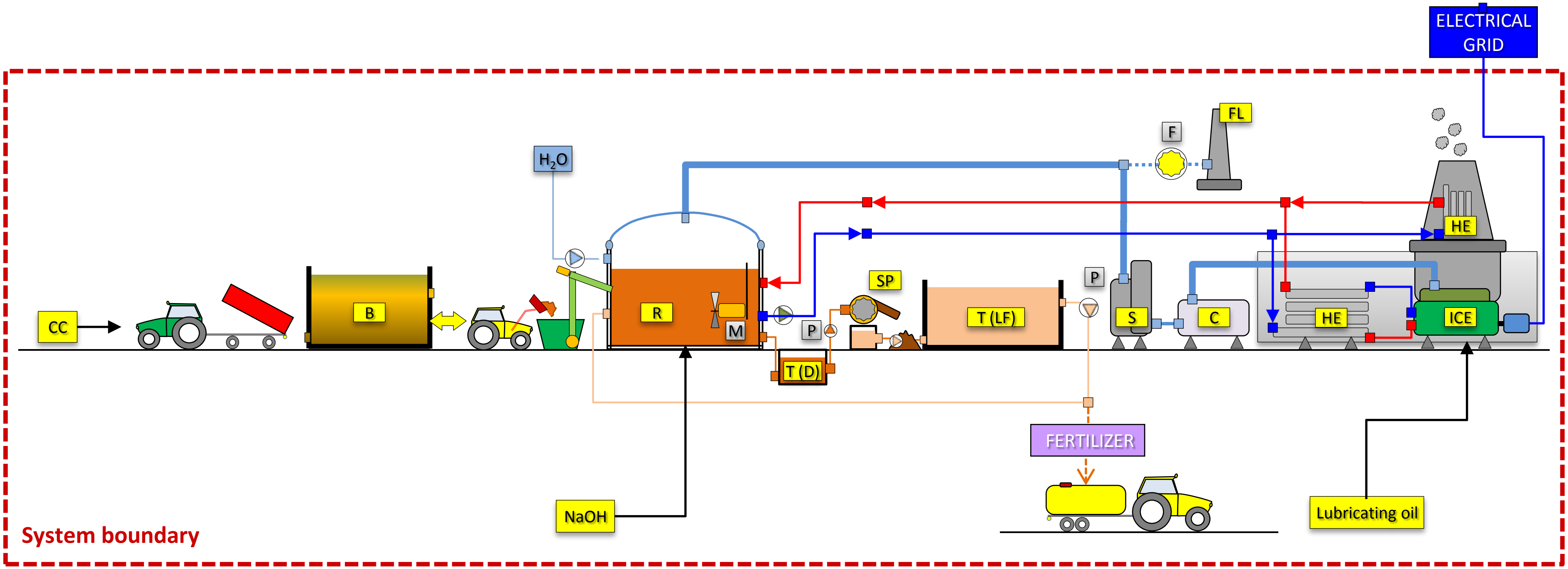
Figure 2



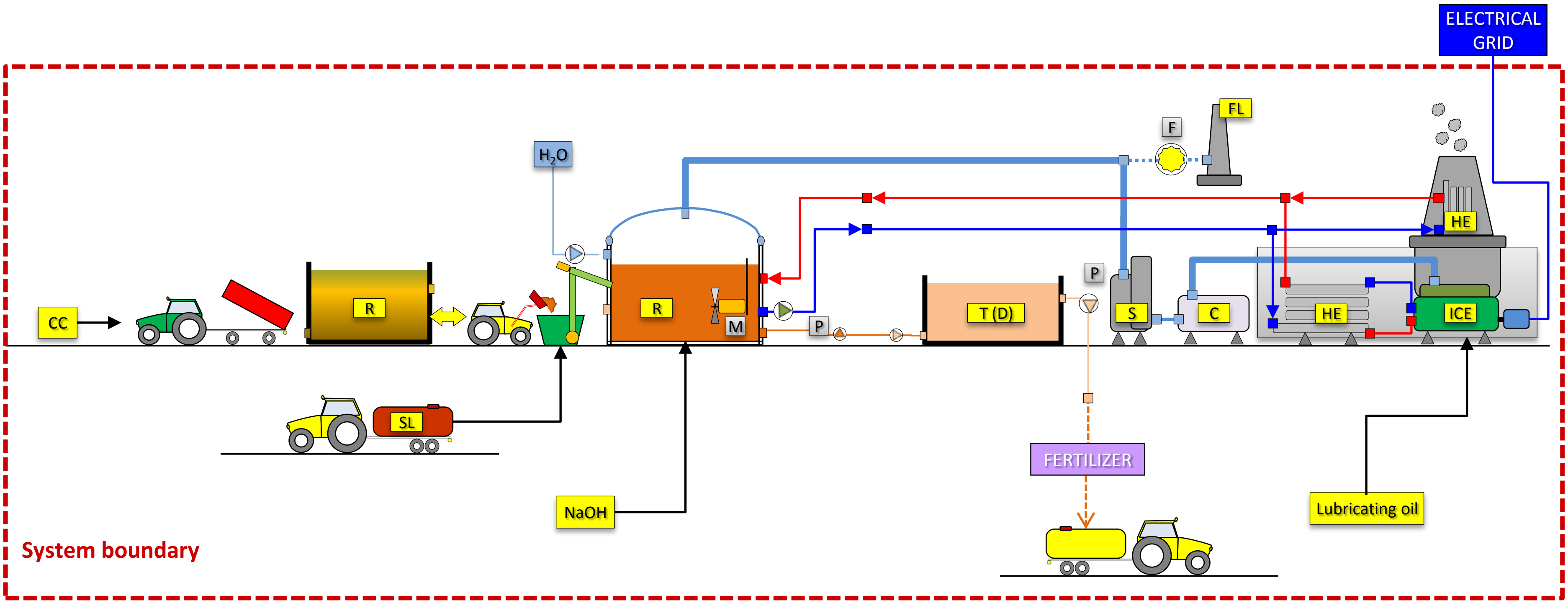
GWP
(kg CO_2 eq/kWh)
1
0.5
0
-0.5
-1
-1.5
-2
Bacenetti and Fiala (2014)
Bacenetti and Fiala (2015)
Bacenetti et al. (2013)
Boulamanti et al., 2013
Capponi et al (2012)
Dressler et al. (2012)
Fantin et al, 2015
Fuchsz and Kohlheb (2015)
Fusi et al. 2016
Gerin et al., 2008
Kral et al. (2015)
Hennig and Gawor, 2012
Ingrao et al. (2015)
Lansche and Müller, 2012
Lijo et al. (2014b)
Meyer-Aurich et al. (2012)
Pehnt (2006)
Rana et al. (2016)
Rehl et al., 2012
Seigl et al., (2011)
Van Stappen et al. (2016)

Figure 3

TOP


ELECTRICAL GRID
FL
F
H_2O
HE
SP
P
P
CC
B
R
M
T (D)
T (LF)
S
C
HE
ICE
FERTILIZER
NaOH
Lubricating oil
System boundary

MIDDLE


ELECTRICAL GRID
FL
F
H_2O
HE
CC
R
R
M
P
T (D)
P
S
C
HE
ICE
SL
NaOH
FERTILIZER
Lubricating oil
System boundary

BOTTOM

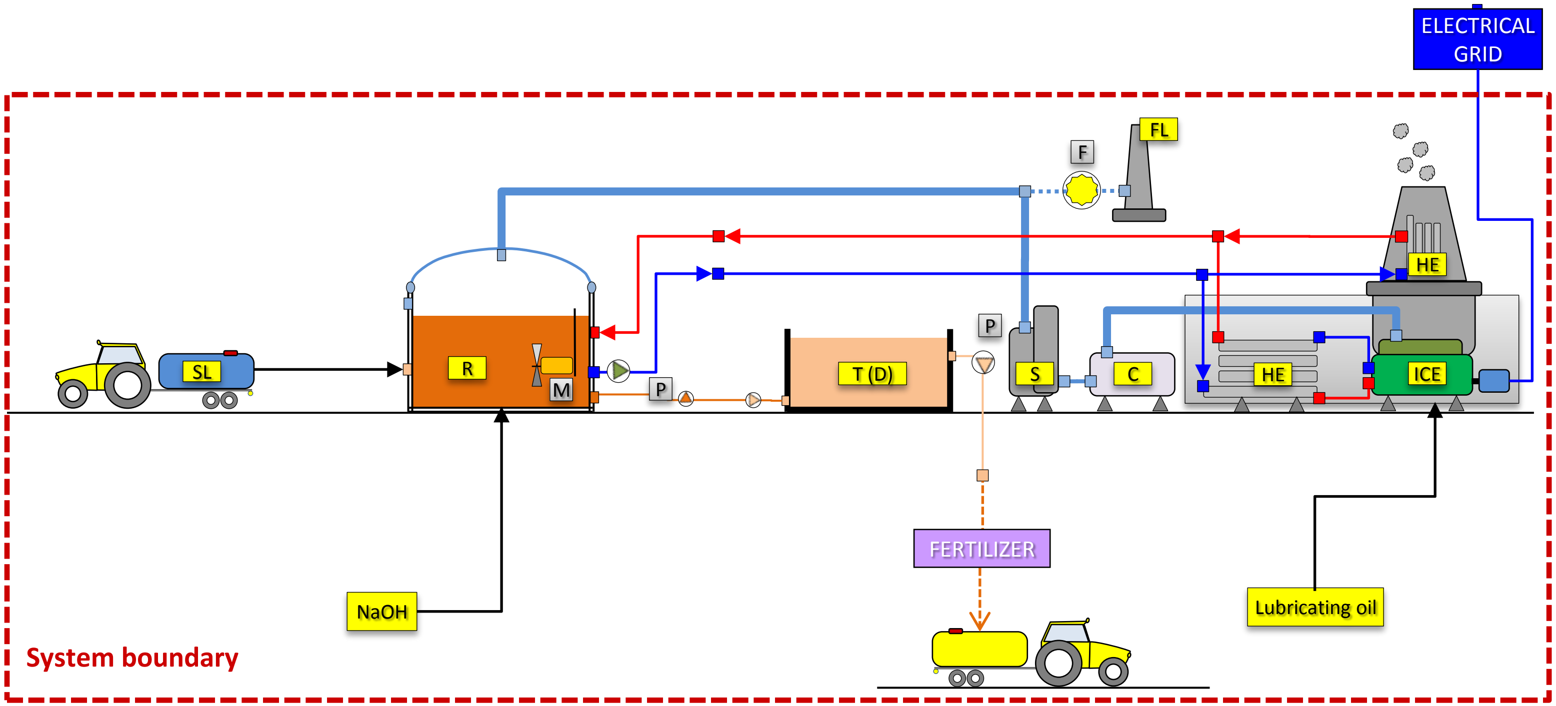
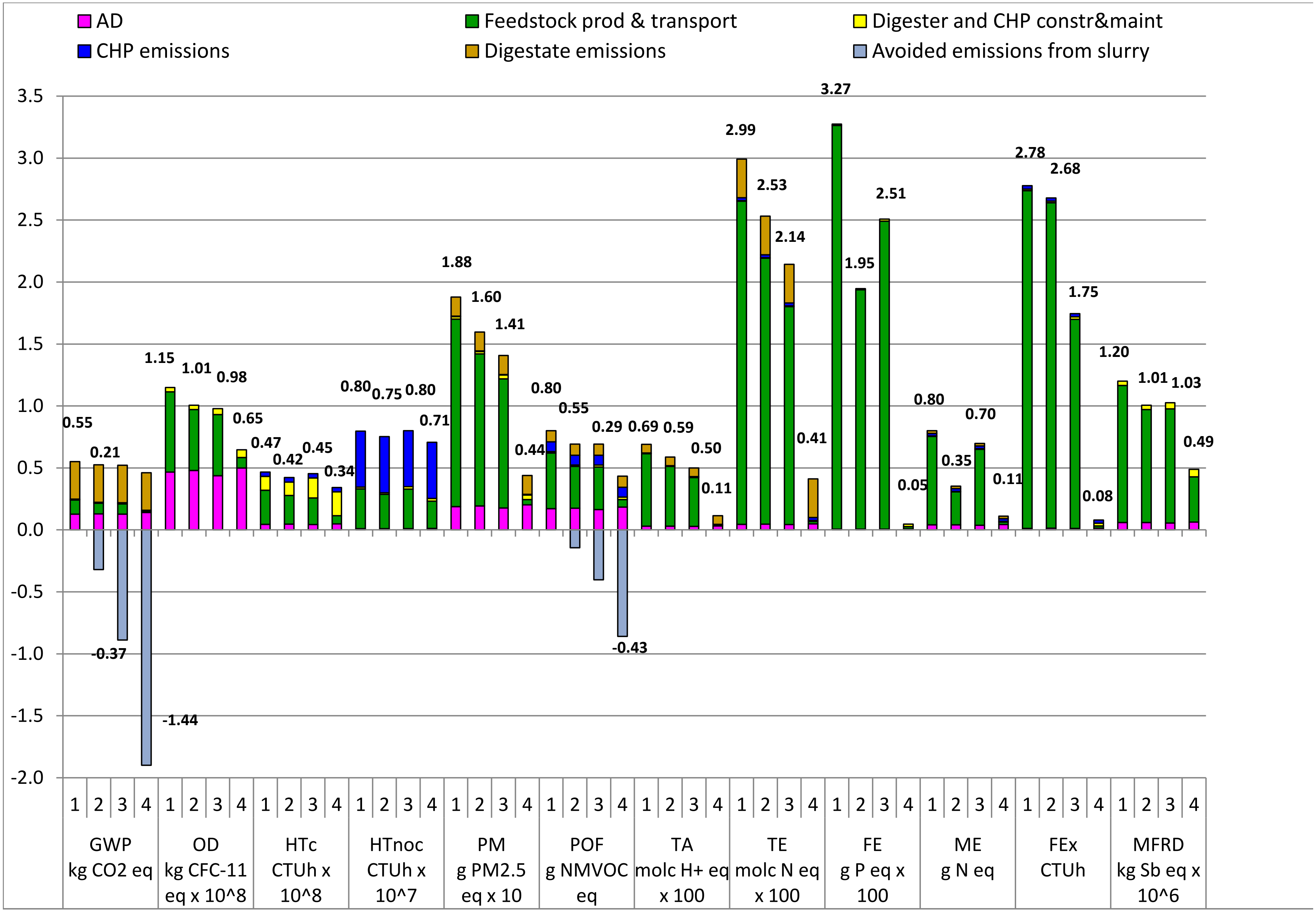

ELECTRICAL GRID
FL
F
HE
SL
R
M
P
T (D)
P
S
C
HE
ICE
FERTILIZER
NaOH
Lubricating oil
System boundary

Figure 4



AD
Feedstock prod & transport
Digester and CHP constr&maint
CHP emissions
Digestate emissions
Avoided emissions from slurry
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.55
0.21
-0.37
-1.44
1.15
1.01
0.98
0.65
0.47
0.42
0.45
0.34
0.80
0.75
0.80
0.71
1.88
1.60
1.41
0.44
0.80
0.55
0.29
-0.43
0.69
0.59
0.50
0.11
2.99
2.53
2.14
0.41
3.27
1.95
2.51
0.05
0.80
0.35
0.70
0.11
2.78
2.68
1.75
0.08
1.20
1.01
1.03
0.49
1 2 3 4
GWP
kg CO2 eq
OD
kg CFC-11 eq x 10^8
HTc
CTUh x 10^8
HTnoc
CTUh x 10^7
PM
g PM2.5 eq x 10
POF
g NMVOC eq
TA
molc H+ eq x 100
TE
molc N eq x 100
FE
g P eq x 100
ME
g N eq
FEx
CTUh
MFRD
kg Sb eq x 10^6

Supplementary material

Table S1 -Feedstock used in the different agricultural AD plants reviewed.

Study	MS	MES	WS	SS	TS	RS	GS	MS	CS	PS	CM	PM	GLY	FW	AIW	AWB	Details about: FW, AIW and AWB
Adelt et al. (2011)	x						x										sugar beet
Bacenetti and Fiala (2014)																	
Bacenetti and Fiala (2015)	x				x				x	X				x			
Bacenetti et al. (2013)	x								x	X							
Bacenetti et al. (2016)														x	x	x	distiller's waste, rapeseed cake, whey permeate, milk fodder, bakery residues
Blengini et al., 2011	x			x	x			x		X							
Borjesson at al. 2015	x				x												hemp, sugar beet, ley crops, wheat (grain)
Borjesson et Berglund. 2007										X	x			x	x	x	ley crops; Straw; tops and leaves of sugar beets; manure; municipal organic waste and food industry waste
Boulamanti et al., 2013	x										x						
Buratti et al. (2013)	x			x	x												
Capponi et al (2012)	x																
Chen et al. (2012)										X				x			
Chevalier at Al. 2005																x	crop residues
Cornejo and Wilkie (2010)																	
Croxatto-										X				x		x	straw, house waste, solid fraction pig slurry

Vega et al., 2014																	
De Meester et al., 2012	x					X	x									x	poultry manure, sugar beet
de Vries et al. (2010)	x								x								
de Vries et al. (2012)	x									X			x			x	
Dressler et al. (2012)	x																
Ebner et al. (2015)									x					x			
Fantin et al, 2015	x			x	x				x								winery waste, sugar beet pulp
Fuchsz and Kohlheb (2015)	x								x								
Fusi et al. 2016	x	x							x						x		
Gerin et al., 2008	x						x			X							
Hahn at Al., 2015	x					X			x								liquid manure; press fluid (fanghi depurazione)
Hamelin et al., (2014)	x									X				x			straw, garden waste, solid fraction
Hamelin et al., 2011										X	x						solid fraction of slurry
Hennig and Gawor, 2012	x										x						Biodegradable waste (non specified)
Ingrao et al. (2015)	x																tritello
Jin et al. (2015)														x			
Jurry et al. (2010)	x		x		x												
Kimming et Al., 2011							x									x	Ley Crop System

Kral et al. (2015)	x									X						x	corn stover
Lansche and Müller, 2011	x						x		x	X							
Lansche and Müller, 2012	x						x			X							
Lijo et al. (2014a)	x									X							
Lijo et al. (2014b)	x				x												
Lijo et al. (2015)	x										x						
Manninen et Al., 2013											x					x	raw materials: manure, waste energy crops, sewage sludge
Meyer-Aurich et al. (2012)			x						x								
Mezzullo et al. (2013)									x								
Morero et al. (2015)															x		
Nzila et al. (2012)																x	animal slurry and manure
Pacetti et al. (2015)	x		x	x													
Patterson et al., 2011														x			OFMSW
Pehnt (2006)	x						x		x	X	x	x					poultry manure
Pertl et al., 2010	x						x			X							
Poeschl et al. (2012)	x		x				x				x			x	x	x	Straw, OFMSW, food residues, pomace, slaughterhouse waste
Pucker et Al. 2013	x						x		x	x	x	x		x	x	x	Grassland biomass, Organic residues (e.g. fruit residues, vegetable residues, fatty residues)
Rana et al.	x																Tritello

(2016)																	
Ravina and Genon (2015)	x									x							
Rehl et al., 2012	x						x		x	x							
Rivas-Garcia et al., 2015										x							
Rodriguez-Verde et al. (2014)										x				x			
Sagastume Gutierrez et al., (2016)										x							
Schumacher et al. (2010)	x				x												
Seigl et al., (2011)	x	x					x		x	X	x	x	x	x	x	x	clover and sunflower silage, chicken manure, oil seed residues, potatos residues, sugar beet cuttings, wheat mill residues, vegetable residues
Siegl at Al., 2012	x	x	x				x		x	X	x	x	x		x	x	energy crops, manure and organic residues in different plant sizes
Styles et al. (2014)	x						x	x			x			x			
Styles et al. (2016)	x						x	x	x	x	x				x	x	potatos residues, sugar beet cuttings, wheat mill residues, bakery residues
Tufvesson et Al., 2013	x														x		distiller's waste; rapeseed cake; whey permeate; fodder milk; bakery residues; sugar beet; ley crops
Van Stappen et al. (2016)	x										x				x	x	Sugar beet tails, Cereal middlings, potatoes wastes
Vu et al., 2015										x		x					
Wang et al (2016)															x	x	
Whiting and Azapagic (2014)	x																cheese whey & fodder beet

Wulf et al., (2006)									x	X							OFMSW
Xu et al. (2015)														x			
Zhang et al. (2015)										x							
Zhang et al. (2013)														x			

MS = maize silage; MES = maize ear silage; WS = wheat silage; SS = sorghum silage; TS = triticale silage; RS = rye silage; GS = grass silage; MSH = mishantus; CS= cattle slurry; PS = pig slurry; CM = cattle manure; PM = pig manure; GLY = Glycerine; FW= food waste; AIW = agro-industry waste; AWB = agricultural waste and by-products; OFMSW = organic fraction municipal solid waste.