# Co-digestion of animal manure and maize: is it sustainable?

– An update –

Alterra Report 2169
ISSN 1566-7197

K.B. Zwart and P.J. Kuikman

# Co-digestion of animal manure and maize: is it sustainable?

This report is based on a project commissioned by SenterNovem in Utrecht (project number: 202107-20-10-001 and order number: 4700013250) and financed by Wageningen UR project KB-10-002-203.

# Co-digestion of animal manure and maize: is it sustainable?

– An update –

K.B. Zwart and P.J. Kuikman

**Alterra report 2169**

Alterra, part of Wageningen UR
Wageningen, 2011

Abstract

Zwart, K.B. and Kuikman, P.J., 2011. *Co-digestion of animal manure and maize: is it sustainable? - an update -*. Wageningen, Alterra, Alterra report 2169. 26 pp.; 6 fig.; 2 tab.; 4 ref.

Co-digestion has attracted increased attention in The Netherlands as a result of a subsidy for electricity that is produced environmentally safe (MEP and SDE subsidy). Production of bio-energy by means of co-digestion turned financially profitable due to this financial support. Co-digestion is the simultaneous digestion of manure and a co-substrate and its conversion into biogas. We report on a methodology to assess the sustainability of bio-energy from co-digestion with emphasis on energy and green house gases (GHG) (Zwart et al., 2006). We have analyzed three cases, i.e. animal manure only or maize only and a mixture of 50% manure and 50% maize. On the basis of the gross 'green gas' and electricity production we calculated efficiencies according to the suggestions cf. Commission Cramer (Anon., 2007). We report that digestion of manure only is most efficient in reducing emissions of greenhouse gases. Digestion of maize without manure produces most energy. In terms of efficiency cf. Commission Cramer a mixture of manure and maize is most efficient. This is more efficient than digestion of maize alone as here emissions of greenhouse gases during crop production limits the efficiency cf. Commission Cramer.

Keywords: co - digestion, greenhouse gases, bio – energy, $CO_2$, $N_2O$, $CH_4$.

ISSN 1566-7197

The pdf file is free of charge and can be downloaded via the website www.alterra.wur.nl (go to Alterra reports). Alterra does not deliver printed versions of the Alterra reports. Printed versions can be ordered via the external distributor. For ordering have a look at www.rapportbestellen.nl.



**Alterra report 2169**
Wageningen, April 2011

# Contents

# Sustainability of co-digestion

Co-digestion has recently attracted increased attention in The Netherlands as a result of a subsidy for electricity that is produced environmentally safe (MEP and SDE subsidy)[1]. Production of bio-energy by means of co-digestion turned financially profitable due to this financial support.

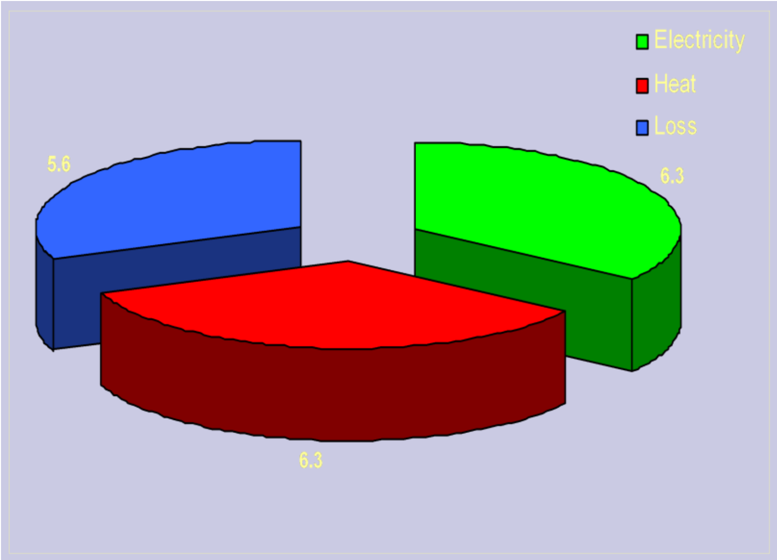


*Figure 1 Energy balance of a 250 kW (e) co-digester with a combined heat-power installation and 7000 full operational hours on an annual basis*[1]

Co-digestion is the simultaneous digestion of manure and a co-substrate and its conversion into biogas. Waste materials or crops specifically grown to produce energy in biodigestors may be used as co-substrate (Figure 1).
Bio-energy is thought to be more sustainable than fossil energy, primarily because no extra $CO_2$ is produced during the production of bio-energy. Instead, the $CO_2$ produced may be re-used immediately by plants, resulting in a more closed carbon-cycle than in case of using fossil fuel for energy production. However, there are more aspects of sustainability related to the production of bio-energy from co-digestion than $CO_2$ alone. First of all, to be sustainable, the overall energy balance should be positive. Crop production and transport of manure and crops are energy consuming processes and in addition, energy is needed for the operation of the digester itself and for transport and application of the non-digestible residues from the process in digestate. Moreover, energy is needed for the production of fertilizers for the crops. So, the overall energy balance of co-digestion will depend on the difference between its total energy production and its energy consumption. Apart from the energy balance, which directly affects the $CO_2$ balance, also other green house gas emission is affected by bio-energy: $N_2O$ is produced during cropping and methane may be produced due to leakage from the digester and during storage of manure and co-substrate. Methane and $N_2O$ are far stronger green house gases than $CO_2$. Also, socio-economic and landscape aspects are important. The importance of economy needs no further explanation. Landscape aspects are important since large scale cropping of energy crops may affect the quality of landscape. However, in this report we will pay no attention to socio-economic or landscape aspects. But still: sustainability of co-digestion is more than just sustainable energy.

We have developed a methodology to assess the sustainability of bio-energy from co-digestion with emphasis on energy and green house gases (GHG) (see Zwart et al., 2006). The elements of this tool and its first results are presented in this document.

[1] The MEP subsidy ended in 2006 and was replaced by a subsidy on sustainable energy (SDE) in 2008 that ended Jan 1st 2011.

**System definition**
The basis of the assessment is a co-digester which produces 500 kW energy in a combined heat and power (CHP) installation, (250 kW electric and 250 kW heat) with an assumed energy conversion efficiency of 35% for both electricity and heat. So, the overall energy conversion efficiency is set at 70%. Further, it is assumed that during the production of biogas, 1% methane will leak from the digester. The number of annual full operation hours is set at 7.000.

**Process steps during co-digestion**
Energy production from co-digestion includes the following steps:
- crop production (field preparation, sowing/planting, fertilization, harvesting and transport)
- manure storage and transport
- co-substrate storage and transport
- digestion (anaerobic digester, combined heat-power (CHP) installation)
- transport and application of digestate

During each of these steps energy is produced or consumed and in a number of the steps methane or $N_2O$ are produced and emitted. The sustainability aspects involved in each step are presented in Figure 2.

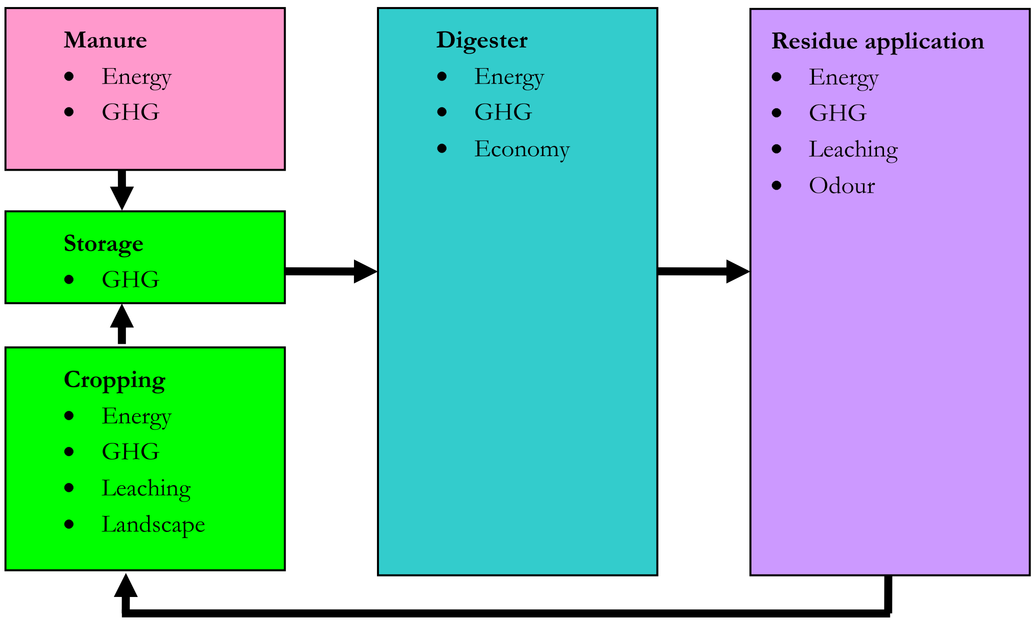


*Figure 2 Process steps and aspects of sustainability of co-digestion*

**Gross energy needed to feed the reactor**
The CHP installation will produce 1.75 million kWh electricity annually and the energy needed for this production equalizes 5 million kWh which is equivalent to 18.0 thousand GJ and approximately 452 thousand $m^3$ methane[2]. Taking the methane leakage into account, an amount of biomass producing 18.2 thousand GJ is needed to feed the digester representing almost 457 thousand $m^3$ methane.

The overall energy balance expressed in thousands of GJ is presented in Figure 1. The total input represents 18.2 thousand GJ, electricity and heat production are 6.3 thousand GJ each. The energy loss is 5.6 thousand GJ.

[2] This calculation is based on the assumption that 1 $m^3$ pure methane is equal to 39.8 MJ (Annex B).

**Volume of manure or maize needed**

A volume of a little over 43 thousand m³ pig slurry or a little over 4071 tons of maize is needed to produce 457 thousands m³ methane. If manure and maize are digested in a 50 : 50% mixture these volumes are 3.720 tons of manure and maize each (see Annex B).

**Key figures and conversion factors**

Key figures concerning energy production and consumption and GHG emissions are given in Figure 3. An additional list of assumptions is presented in Annex B.

**Savings in GHG emissions**

Savings in GHG emissions can be divided in energy related savings and other GHG related savings.

1. *Energy related GHG savings*
   Co-digestion produces a certain amount of net energy in the form of electricity and heat. This amount can thus be saved from using fossil energy. It represents an equivalent amount of $CO_2$, which can be calculated using specific $CO_2$ emission factors for electricity and heat (Annex B). Details of the calculation of energy related GHG savings are presented in Annex C.

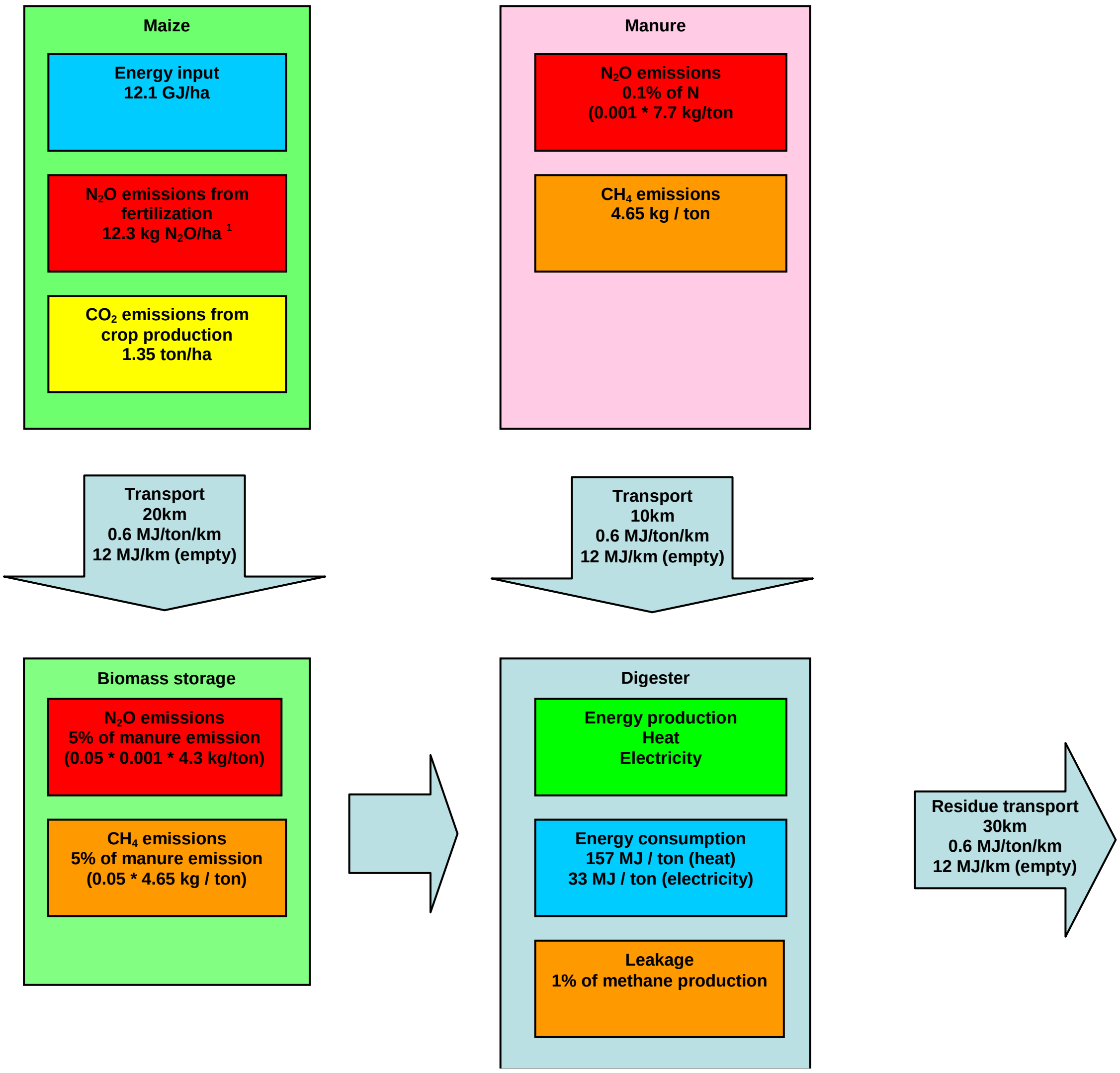


*Figure 3 Key figures concerning energy production and consumption and GHG emissions (direct and indirect emissions)*

2. *Other GHG related savings*
   Storage of manure is accompanied by methane production and methane emission. Digestion instead of storage of manure may therefore lead to a reduction of GHG emission. It is assumed that digestion of manure will result in a 95% reduction of GHG emission.

However, co-digestion is also accompanied by the production of other GHG. A certain amount of biogas will leak from the digester. Moreover, the use of maize as a co-substrate may increase GHG emission, predominantly as a result from $N_2O$ production accompanied with fertilizer use during crop production. The net saving related to GHG can be calculated using specific $CO_2$ emission factors for methane and $N_2O$ (Annex B). Details of the calculation of other GHG related savings are presented in Annex C.

**Green gas**
One of the restrictions in the current execution and implementation of co digestion in the Netherlands is the fact that only the net electricity output is supported financially. Electricity production inevitably is accompanied by heat production. Only a small part of this heat can be used successfully in the rural areas of farm-based digesters. So, the overall energy efficiency of farm based digesters is rather low. If the produced gas would be used more efficiently elsewhere the overall energy efficiency of co digestion could possibly be increased.
Green gas can be produced by co-digestion without the typical conversion losses of a CHP installation. If 'green' gas would be the end product of the co-digestion, the net energy output is possibly higher than in case of electricity production.

We have assumed that the net energy production from green gas production by co-digestion is equal to the gross energy production of 18.2 thousand GJ in a CHP installation (Figure 1). Of course one must bear in mind that gas consumption outside the digester will also result in conversion losses and these may vary widely and depend on application. Also, the process of green gas production requires a certain amount of energy. The major energy consuming processes in case of green gas production are related to: crop production, transport and energy consumption by the digester. The amounts of energy represented by these processes are in fact not different from the situation including a CHP installation. In addition, energy is needed to upgrade the quality of biogas prior to its application in the gas infrastructure.

Savings in green gas related GHG emissions have been calculated. Details of the calculation of energy related savings are presented in Annex C. Note that the energy needed to upgrade biogas to earth gas quality, necessary for the inlet in the gas infrastructure, has not been included. The other GHG related savings are the same as described for CHP.

**Efficiency cf. Commission Cramer**
The Dutch Commission Cramer has developed criteria to evaluate the efficiency of green energy in terms of prevention of $CO_2$ emission. Green energy efficiency is calculated by dividing its accompanied $CO_2$ reduction by the $CO_2$ emission from a same amount of energy using fossil sources (reference value). Green energy is regarded efficient at outcomes above 70% as compared to the reference value.
The fossil energy reference value in this study was calculated on the basis of 6.3 GJ of electricity and 6.3 GJ of heat, using specific emission factors for electricity and heat from fossil sources (Annex B). The reference value for the efficiency calculation cf. the Commission Cramer was 1466 tons of $CO_2$.
We have calculated the GHG efficiency for the co-digestion of a mixture of 50% manure and maize both after including and excluding the GHG emission from crop production.

**Three different cases in co-digestion**

In the next paragraphs the production of energy and the production and emission of green house gases methane and $N_2O$ will be described for three different cases:

I. digestion of 100% manure (pig slurry) alone.
II. digestion of 50% manure and 50% maize.
III. digestion of 100% maize.

**Case I: 100% manure**

An amount of 43.144 tons manure is needed to feed a 500 kW CHP installation. The production and consumption of energy and the production of methane and $N_2O$ during the digestion of manure alone is presented in Figure 4.

**Energy**

The net energy (summation from Figure 4) produced from manure alone is 3.4 thousand GJ. Heat production is completely needed for heating the manure during digestion and a relatively small amount of energy for transport is needed.

**Methane and $N_2O$**

The production of the non - $CO_2$ greenhouse gases methane and $N_2O$ from manure storage is 10.0 tons and 26.1 kg, respectively. These figures are based on the assumption that utilization of manure for biogas production will lead to a 95% reduction in the emission of these gases from manure storage. The production and emission of methane via 1% leakage from the digester is 3.2 tons.

**Savings in GHG emissions**

The energy and GHG related saving in $CO_2$ emissions for 100% manure are 820 and 4013 tons of $CO_2$, respectively (Table 2). Expressed in terms of efficiency cf. the Commission Cramer, digestion of manure alone has an efficiency of 100% or more compared to electricity production from fossil fuel. This high efficiency is almost entirely due to relatively high avoided emissions of $CH_4$ from manure storage.

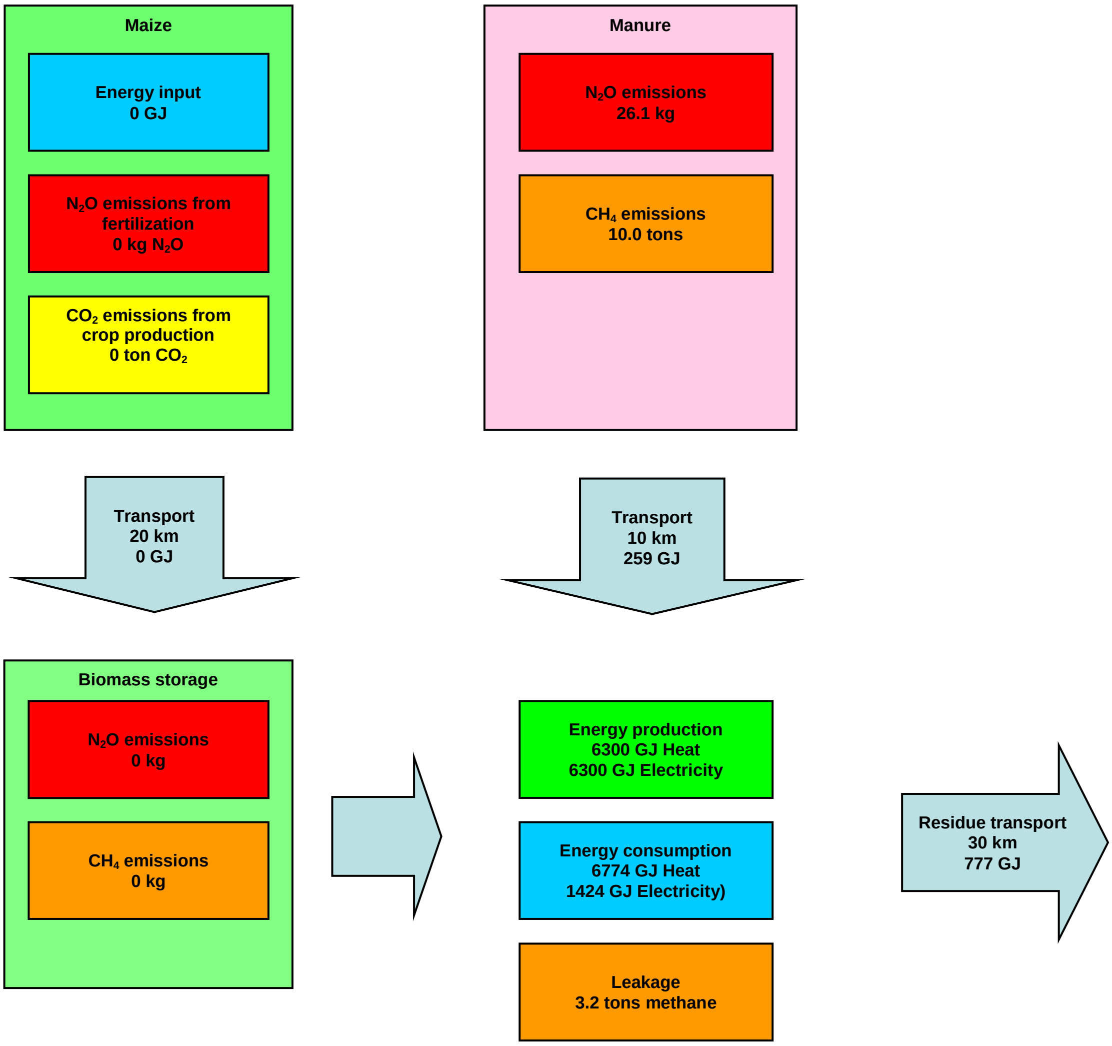


*Figure 4 Production and consumption of energy and the production of methane and $N_2O$ during the digestion of 100% manure*

**Case II: 50% manure and 50% maize**

An amount of 3.720 tons of manure and 3.720 tons of maize are needed to feed the digester. The production and consumption of energy and the production of methane and $N_2O$ during the digestion of a mixture of (50%) manure and (50%) maize is presented in Figure 5.

**Energy**

The net energy production is 10.0 thousand GJ. The total heat consumption by the digester is far lower than in case of manure alone, due to the far smaller volumes of manure and maize involved. Energy needed for cropping and transport of crop, maize or digester residue constitute only minor entries in the overall energy balance.

**Methane and $N_2O$**

Methane emissions are 0.9 and 0.6 tons from manure storage and crop storage respectively and 3.2 tons from the digester. $N_2O$ emissions are 2.2 and 1.3 kg from manure storage and crop storage respectively and 670 kg from cropping. The emission factors for methane and $N_2O$ from crop storage was an assumed value (the average of the factors for pig and cattle manure). The same 95% reduction as for manure was assumed in case of co-digestion instead of long-term storage.

### Savings in GHG emission

The energy and GHG related saving in $CO_2$ emission for 50% manure and maize are 1338 and -167 tons of $CO_2$, respectively (Table 2). Expressed in terms of efficiency cf. the Commission Cramer, digestion of manure and maize is 81% as efficient as electricity production from fossil fuel. The efficiency is > 100% if GHG emission from crop production is not taken into account. However, the efficiency drops to 61% if GHG savings from heat production are excluded from the calculation.

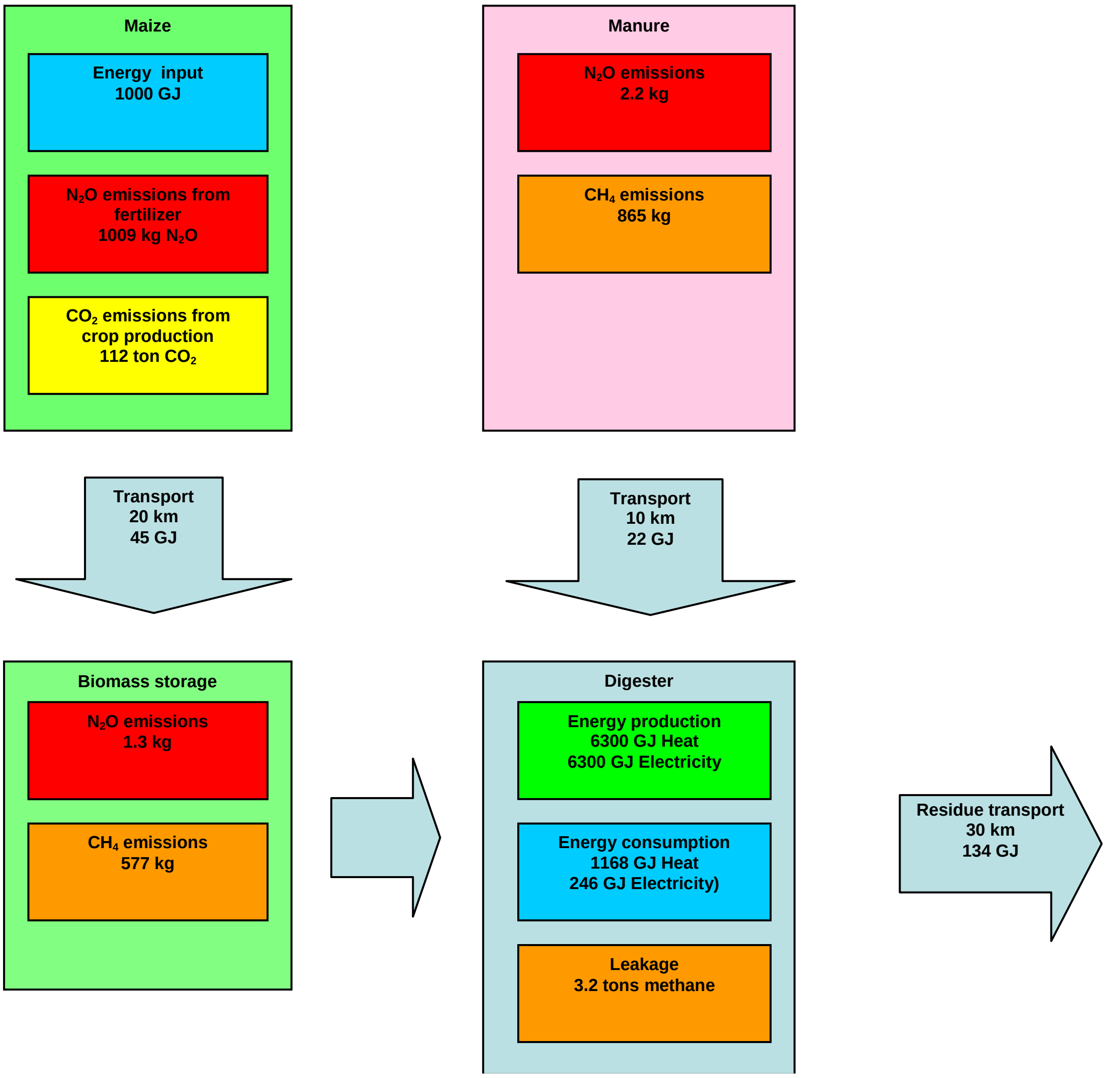


*Figure 5 Production and consumption of energy and the production of methane and $N_2O$ during the digestion of 50% manure and 50% maize*

### Case III: 100% maize

An amount of 4.071 tons of maize is needed to feed the digester in case of 100% maize.
The production and consumption of energy and the production of methane and $N_2O$ during the digestion of maize alone is presented in Figure 6.

### Energy

The net energy production is 10.6 thousand GJ. The major difference compared to the situation with 50% manure is the total volume of co-substrate needed (4.071 versus 7.440 tons). Again, energy for cropping and transport form only minor posts in the overall energy balance.

**Methane and $N_2O$**

Methane emissions are 0.6 tons from crop storage and 3.2 tons from digester leakage. $N_2O$ emissions are 733 kg from required fertilization of the crop for co-substrate and 1.4 kg from crop storage before actual digestion.

**Savings in GHG emission**

The energy and GHG related saving in $CO_2$ emission for 100% maize are 1387 and -562 tons of $CO_2$, respectively (Table 2). Expressed in terms of efficiency cf. the Commission Cramer, digestion of maize alone is 57% as efficient as electricity production from fossil fuel.

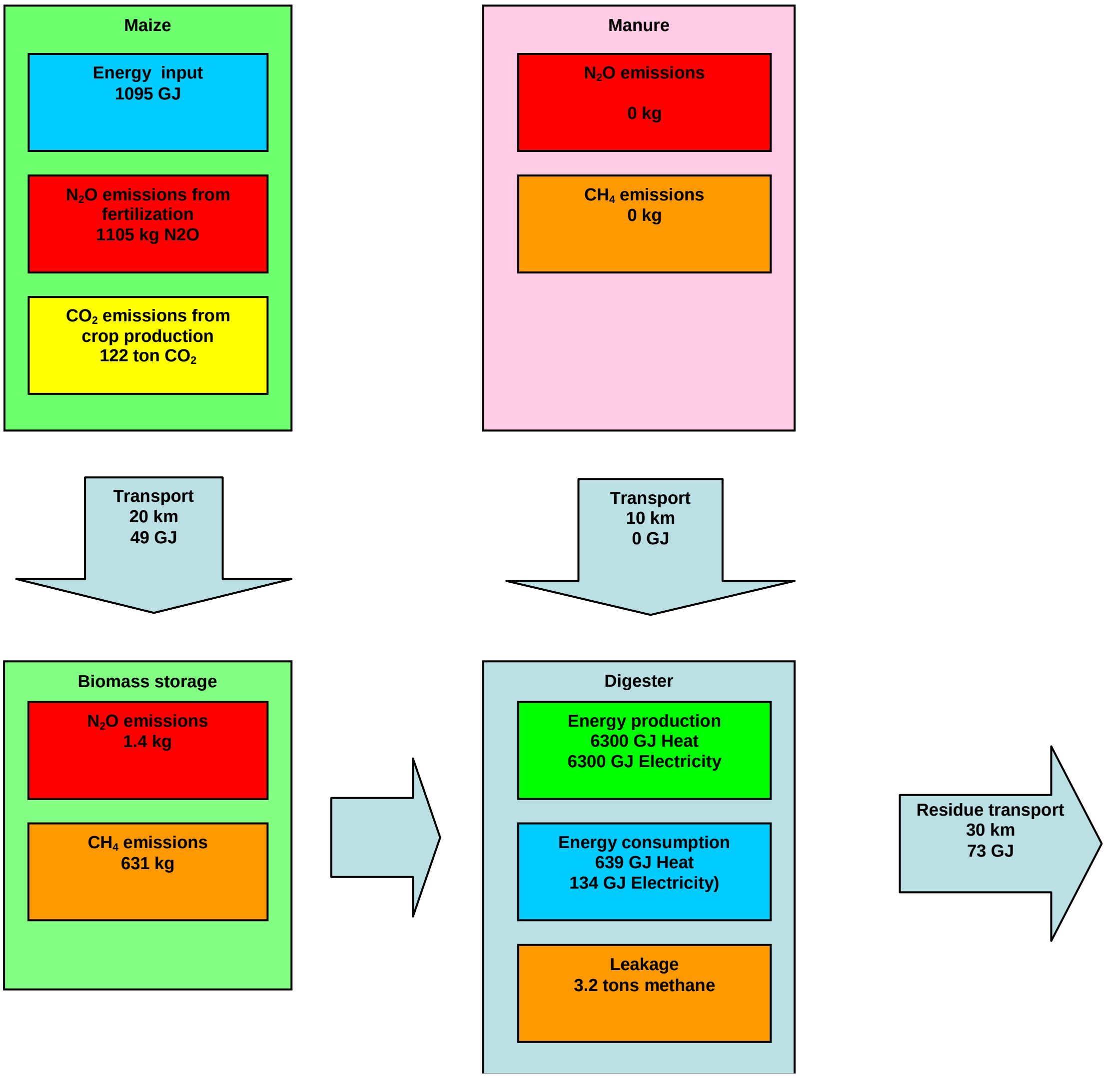


*Figure 6 Production and consumption of energy and the production of methane and $N_2O$ during the digestion of 100% maize*

**Green gas**

The savings in GHG emission in case of green gas production are lower than for CHP for all situations described (Table 2). The far higher $CO_2$ emission factor for electricity from fossil fuels explains the higher GHG savings in case of CHP.

# Discussion and conclusions

*Energy*
The digestion of maize alone results in the highest net energy production (10.6 thousand GJ) using CHP, closely followed by a mixture of 50% manure and 50% maize (10.0 thousand GJ). The small difference may surprise somewhat since one would probably expect 50% lower energy production in case of the mixture. That would indeed be the result in case of a digester of a fixed volume. However, we used a fixed CHP production of 500 kW and then the digester volume varies with the energy content of the substrate. The energy content of maize is approximately 10 times higher the energy content of manure, and the total volume of the co-substrate in case of the mixture is almost twice as high as for maize alone. Accordingly the net energy production of 100% maize is almost similar to that of the mixture of manure and maize. The net energy production from manure alone is far lower than for the mixture due to the energy consumption of the digester.

*Reduction of green house gas emissions*
For the calculation of the reduction of green house gas emissions by using co-digestion two different aspects are important:
1. emission reduction as a result reduction from manure storage:
2. emission reduction as a result of reduction of fossil energy consumption.

*Non $CO_2$ greenhouse gas emission*
The total GHG production from 100% manure, in case it would have been stored instead of used for biogas production would be 200 tons of methane and 522 kg of $N_2O$, equivalent to a total amount of 4375 tons of $CO_2$[3]. In the case with 50% manure and maize the total GHG emission would be 17 tons of methane and 45 kg of $N_2O$, equivalent to 377 tons of $CO_2$.

In Table 1, we present the production of GHG emission during co-digestion in terms of $CO_2$ equivalents for the three cases described above. We conclude that:
1. Prevention of non $CO_2$ GHG emissions from manure storage leads to the highest emission reduction of ton $CO_2$ equivalents.
2. Co-digestion of 50% *maize and manure* and of *100% maize* results in higher non-$CO_2$ GHG emissions ($CH_4$ and $N_2O$) than in case of manure alone due to the high emissions during crop production.
3. Application of manure in co-digestion is less attractive in terms of energy produced and therefore less attractive in terms of financial profit compared with digestion of maize alone.
4. The production of green gas for utilization in industry and households rather than utilization of the gas 'on farm' offers realistic options to further improve the performance of co-digestion in terms energy production; this only holds if such 'off farm' energy conversion from green gas is more efficient than the 'on farm' conversion of the gas.

*Energy related greenhouse gas emission*
The annual production of 6.3 thousand GJ electricity from fossil fuel is equivalent to 1466 tons of $CO_2$, assuming a 40% conversion efficiency for electricity and a $CO_2$ conversion factor based upon a standard mix

[3] See Annex A for conversion of methane and nitrous oxide to $CO_2$ equivalents based on their global warming potential

of coal and gas (Annex B). The savings in $CO_2$ equivalents as a result of co-digestion for the three different cases in terms of both energy and GHG is presented in Table 2.
We conclude that:

1. The *energy related* reduction of $CO_2$ emissions from displaced fossil fuel is greatest during CHP produced electricity and heat from 100% maize.
2. The *energy related* reduction of $CO_2$ emissions is much smaller in case of 100% manure use and CHP, since in this case the energy consumption by the digester itself is very large due to a relatively large reactor volume needed to digest all the manure.
3. In contrast, the highest reduction in *total* greenhouse gas emissions, now in terms of $CO_2$ equivalents, occurs in the case of 100% manure. This is almost entirely due to a lower emission of methane and $N_2O$ from manure storage. A reduction of 95% was assumed in case of digestion than in case of prolonged storage of manure without digestion.
4. The overall balance for all three cases we have considered shows net avoiding of emissions of greenhouse gases ($CO_2$, $CH_4$ and $N_2O$) and these range from 825 for digestion of 100% maize to 4833 ton
   $CO_2$ equivalents for digestion of 100% manure (table 2). Even if the reduction of emissions from storage would be much smaller, digestion of only manure would still lead to the highest reduction of GHG emissions (e.g. 2864 tons of $CO_2$ in case of a reduction of only 50%).
5. The production of green gas for utilization in industry and households rather than utilization of the gas 'on farm' offers no realistic options to further improve the performance of co-digestion in terms of GHG emission reduction. But this is entirely due to the used emission factors for electricity from fossil fuel.
6. On the basis of the gross gas production (Figure 2) and the calculated efficiencies according to the suggestions cf. the Commission Cramer (Anon., 2007) only the cases 100% manure and manure plus maize (50+50%) meet the 'Efficiency criterion cf. the Commission Cramer'. Results for our case III, 100% maize do not meet this 70% criterion. In the case of 100% maize, the higher emissions of greenhouse gases during production of the co-substrate explain the lower value for the 'Efficiency criterion cf. the Commission Cramer'. The case 100% manure apparently meets the 'Efficiency criterion cf. the Commission Cramer' but then, only little net energy is produced and savings in terms of GHG are due to avoided emissions from manure storage.

It is difficult to decide when co-digestion is a sustainable production form of energy. From an energy point of view a mixture of manure and maize seems to be preferable over manure alone. But from a reduction of GHG emissions point of view, manure alone is the best option.

One should realize that a number of parameters used in the current study are rather uncertain e.g. the reduction of GHG emissions due to digestion of manure, the emission factor for crop storage and the emission as a result from digester leakage.
Only in case of digestion of freshly produced manure, a reduction factor of 95% seems realistic. In practice, however, manure will probably always be stored for a certain period of time, before it is transferred to a digester.
Methane and $N_2O$ emissions from crop storage are in fact unknown and should be established if possible. The same holds for digester leakage. In modern digesters leakage has been reduced dramatically after the introduction of a second phase reactor. However, in case methane production has not come to a complete halt after the second phase, still an unknown amount of methane may be emitted from the residue at application of the digestate. Information on the quantity of such methane emission is badly needed.

*Table 1 Production of non $CO_2$ greenhouse gas emissions during co-digestion (in $CO_2$ equivalents, tons per year) for three different cases as described above*

| | | | | **Manure 100%** | **Manure Maize 50 : 50%** | **Maize 100%** |
|---|---|---|---|---|---|---|
| Cropping | | | | 0 | 430 | 471 |
| Storage | A | Manure | Methane | 211 | 18 | 0 |
| | B | | $N_2O$ | 8 | 1 | 0 |
| | | Crop | Methane | 0 | 12 | 13 |
| | | | $N_2O$ | 0 | 0 | 0 |
| Digester leakage | | | Methane | 68 | 68 | 68 |
| Transport | | Manure | | 19 | 2 | 0 |
| | | Crop | | 0 | 3 | 4 |
| | | Residue | | 57 | 10 | 5 |
| Total emission | C | | | 362 | 544 | 562 |
| Emission from manure without co-digestion | D~(A+B)/0.05 | | | 4375 | 377 | 0 |
| Reduction | D-C | | | 4013 | -167 | -562 |

*Table 2 Savings in $CO_2$ equivalents (tons per year) as a result of co-digestion for the three different situations in terms of both energy and greenhouse gases for co-digestion using CHP and green gas*

| | | **Savings due to co-digestion and CHP** [4] | | | **Savings due to green gas production** | | |
|---|---|---|---|---|---|---|---|
| | | **100% manure** | **50% manure and maize** | **100% maize** | **100% manure** | **50% manure and maize** | **100% maize** |
| Energy related savings [5] | A | 820 | 1338 | 1387 | 362 | 880 | 929 |
| Non $CO_2$-GHG related savings (Table 1) | B | 4013 | -167 | -562 | 4013 | -167 | -562 |
| Net savings | A+B | 4833 | 1171 | 825 | 4375 | 713 | 368 |
| Reference value ($CO_2$ produced from fossil energy) [6] | C | 1466 | | | | | |
| Efficiency cf. Commission Cramer[7] | 100 * (A+B)/ C | >100% | 81% | 57% | | | |
| Efficiency cf. Commission Cramer [8] without GHG from crop production | | | >100% | | | | |
| Efficiency cf. Commission Cramer without heat utilization from on farm CHP [9] | | | 61% | | | | |

---

4 Calculation for 'savings due to CHP' is different from the calculation on the basis of the suggestion by Anon (2006, 2007); in the latter the electricity production is the basis whereas we take electricity and heat together since that is the strength of CHP. For 'green gas' all energy is in the form of gas; it fits the Commission Cramer definition for biofuel.

5 $CO_2$ produced from fossil fuel to produce the same net amount of electricity and heat as from co-digestion, using specific emission factors for electricity production from a standard Dutch fuel mix and for heat production.

6 $CO_2$ produced from fossil fuel to produce 6.3 thousand GJ electricity with 40% efficiency and 6.3 thousand GJ heat using specific emission factors for electricity production from a standard Dutch fuel mix and specific emission factors for heat production.

7 See foot note 1

8 Here we indicate the *Efficiency of the Commission Cramer* for the special case in which for specific reasons emissions of greenhouse gases associated with crop production do *not* have to be included in the analyses. In our analyses so far, we have assumed that maize is specifically produced for application in co-digestion for energy production and that all emissions of greenhouse gases associated with crop production are to be included in the analyses. Emissions during production would not have to be included i.e. to prevent double counting in a case when residues are used and emissions have been accounted for under agricultural production. In case efforts during crop production do result in effective mitigation of emissions of (energy) crop production related greenhouse gases from fertilizer application, soil or residue management the outcome would be intermediate.

9 Here we indicate the *Efficiency of the Commission Cramer* for the special case in which the heat produced in the digester is not used apart from the fraction of the heat needed to operate the digester itself. As a result the energy related savings drop from 1338 to 1050 tons $CO_2$ equivalents and the efficiency drops from 81% to 61%.

# References

Anon., 2006. Criteria voor duurzame biomassa productie. Eindrapport van de projectgroep 'Duurzame productie van biomassa'. Task Force Energietransitie, SenterNovem, Utrecht. 40 pp. http://www.senternovem.nl/mmfiles/Cramer_juli2006_tcm24-328323.pdf (in Dutch).

Anon., 2007. Toetsingskader voor duurzame biomassa. Eindrapport van de projectgroep 'Duurzame productie van biomassa'. Task Force Energietransitie, SenterNovem, Utrecht. 62 pp. http://www.senternovem.nl/duurzameenergie/publicaties/publicaties_bio-energie/toetsingskader_voor_duurzame_biomassa.asp (in Dutch).

Bosselaar, L. and T. Gerlagh, 2006. Protocol monitoring duurzame energie, update 2006. Senter Novem 2DEN0611, pp. 67 (in Dutch).

Zwart, K.B., D.A. Oudendag, P.A.I. Ehlert and P.J. Kuikman, 2006. Duurzaamheid co-vergisting van dierlijke mest. Alterra Wageningen UR, Nederland. Alterra rapport 1437 http://www.senternovem.nl/mmfiles/Duurzaamheid%20co-vergisting%20van%20dierlijke%20mest_tcm24-216864.pdf pp. 72. (in Dutch).

# Annex A Glossary

| | |
|---|---|
| GHG | Green House Gas |
| GWP | Global Warming Potential (kg $CO_2$ / kg)<br>$CO_2$ = 1<br>$CH_4$ = 21<br>$N_2O$ = 310<br>$N\text{-}N_2O$ = 488 |
| CHP | Combined Heat and Power (electricity) |

# Annex B Assumptions

*Digester and co-digestion: characteristics and dimensions*

| Key entry/number | Value (units) |
|---|---|
| Dimensions CHP installation | 500 kW |
| Annual full operational hours | 7000 |
| Total electricity production | 3.5 * 10^6 kWh |
| Methane | 39.8 MJ/$m^3$ |
| Conversion MJ to electricity | 3.6 MJ/kWh |
| Overall efficiency | 70% |
| Methane in $m^3$ per $m^3$ pig slurry | 19.25 $m^3$ biogas or 11 $m^3$ methane |
| Methane produced per ton maize | 204 $m^3$ biogas or 112 $m^3$ methane |
| Heat consumption digester 500 kW (250 $kW_e$ and 250 $kW_{thermal}$)[10] | 157 MJ per $m^3$ |
| Electricity consumption digester 500 kW | 33 MJ per $m^3$ |
| | |
| Yield maize | 45.0 ton fresh weight per ha |
| Cropping energy | 1.35 ton $CO_2$ eqv. per ha [11] |
| $N_2O$ emission for maize | 8.2 kg $N_2O$ per ha direct (2.542 ton $CO_2$ per ha) and 4.1 kg $N_2O$ indirect (1.271 ton $CO_2$ per ha) |
| | |
| Transport (truck without load) | 12 MJ per km |
| Transport (load) | 0.8 MJ per ton per km |
| Emission transport | 0.073 kg $CO_2$ per MJ or 0.88 kg $CO_2$ per km |
| | |
| Conversion electricity to $CO_2$ using standard fossil fuel mix | 0.0694 kg $CO_2$ per MJ |
| Conversion heat to $CO_2$ | 0.056 $CO_2$ per MJ |
| Conversion $CH_4$ (fuel) to $CO_2$ | 2.19 kg $CO_2$ per $m^3$ $CH_4$ |
| Reduction factor methane emissions from manure storage due to digestion | 95 % |
| Methane emission from manure storage | 4.95 kg per ton |
| Methane emission from maize storage | 3.1 kg per ton [12] |
| $CO_2$ equivalents methane | 21 kg $CO_2$ per kg methane |
| $CO_2$ equivalents $N_2O$ | 488 kg $CO_2$ per kg N- $N_2O$ |

[10] This number is the demand for a farm based digester of 500 kW; for larger facilities this heat demand drops to 50% of this value

[11] Including energy needed for seed and pesticide production, fertilizer production and cropping (Zwart et al., 2006)

[12] Assumed value, calculated as the average for pig manure and cattle manure (Zwart et al., 2006)

# Annex C Calculations

**Energy related GHG savings CHP (GHGe)**
GHGe savings = GHGe ((A + B) – (C + D)
A = net electricity production = gross electricity production – electricity consumption digester (GJ)
GHGe A = A / efficiency conventional plant * GHG emission factor electricity = A/ 0.4 * 0/0694 (ton $CO_2$ eqv.)

B = net heat production = gross heat production – heat production digester (GJ)
GHGe B = B * GHG emission factor heat = B * 0.056 (ton $CO_2$ eqv.)

C = transport (manure + crop + residue) (GJ)
GHGe C = C * GHG emission factor transport = C * 0.073 (ton $CO_2$ eqv.)

D = energy related to crop production (fertilizer production and cropping)
GHGe D = ha maize * GHG emission factor cropping energy = ha maize * 1.35 (ton $CO_2$ eqv.)

**Energy related savings Green gas**
GHGe savings = GHGe (F – (C + D)
F = methane production digester ($m^3$)
GHGe F = F * GHG emission factor fuel energy from methane = F * 0.0219 (ton $CO_2$ eqv.)

C and D, see above

**Other GHG related savings (GHGo)**
GHGo savings = GHGo (G) – GHGo (H + J + K)

G = reduction of manure storage (95%)
GHGo G = tons of manure * methane emission factor manure storage * (1-reduction factor) * CO2 equivalents methane = tons of manure * 4.65 * (1- 0.95) * 21 (ton $CO_2$ eqv.)

H = digester leakage (1%)
GHGo H = methane production digester (tons) * 0.01 * $CO_2$ equivalents methane = methane production digester * 0.01 * 21 (ton $CO_2$ eqv.)

J = crop storage
GHGo J = crop production (tons) * methane emission factor crop * (1-reduction factor) * $CO_2$ equivalents methane = crop production (tons) * 3.1 * (1-0.95) * 21 (ton $CO_2$ eqv.)

K = direct and indirect crop emissions
GHGo K = ha crop production * (direct N-$N_2O$ emissions per ha + indirect N-$N_2O$ emissions per ha )/1000 * $CO_2$ equivalents N- $N_2O$ = ha crop production * (8.2 + 4.1) * 488 (ton $CO_2$ eqv.)