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LIFE CYCLE ASSESSMENT OF BIOGAS SYSTEMS IN THE EUROPEAN CONTEXT

Analisi del ciclo di vita di scenari di produzione ed utilizzo di biogas nel contesto europeo

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NOMENCLATURES

AD: Anaerobic Digestion

CED: Cumulative Energy Demand

CEU: Cleaner Energy Unit

CH: Swiss situations

CHEM: chemical absorption

CHP: Combined Heat and Power

CNG: Compressed Natural Gas

CEU: Cleaner Energy Unit

CSTR: Continuous Stirred Tank Reactor

DM: Dry Matter

ELCD: European Life Cycle Database

EU: European Union

GHG: greenhouse gases

GWP: Global Warming Potential

HHV: Higher Heating Value

HRT: Hydraulic Retention Time

IET: Institute of Energy and Transport

ILCD: International Reference Life Cycle Data System

ISO: International Standardisation Organisation

JRC: Joint Research Centre

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

LHV: Lower Heating Value

NMVOC: Non-Methane Volatile Organic Compounds

PAF: Potentially Affected Fraction of species

PF: Plug Flow reactor

PHY: physical absorption

PSA: Pressure Swing Adsorption

PWS: Pressure Water Scrubbing

RED: Renewable Energy Directive 2009/28/EC

RER: mix of situations of European countries

TS: Total Solids

UCTE: Union of Co-ordination of Transmission of Electricity

VFA: Volatile Fatty Acids

VS: Volatile Solids

ABSTRACT

The study analysed the environmental performance from cradle to grave of different biogas production and utilisation scenarios with a Life Cycle Assessment (LCA) approach. The analysis aimed at considering on the whole some issues of biogas systems that other studies did not included in details: firstly, the leakages of methane from different source points in the production chain and in the plant; secondly, the specific nutrient content in the digestate, that can affect the emissions that occur during its management and the possibility to use it as substitute of chemical fertilisers; thirdly, the inclusion of credits that manure digestion can grant. In fact, these criticalities can influence the amount of the greenhouse gas (GHG) emissions that have to be accounted for. The study underlines how these are able to affect the sustainability of biogas systems.

New processes were created with calculations and data found in the international literature to include these issues in the LCA analysis, performed in accordance with ISO and ILCD recommendations. Reference systems and complete inventories were taken from Ecoinvent 2.2 database after a critical analysis.

This study showed that even though the environmental policies encourage biogas production and utilisation in order to assure GHG savings, in real plants some techniques are responsible for higher emissions than the reference system. The highest greenhouse gas emissions were attributed to the pathways in which energy crops are used as feedstock and the digestate is stored in open air, in which upgrading technologies with low efficiency in methane recovering are used and in which the agricultural effort to produce the feedstock is high. The worst scenario resulted in emissions of CO_2 equivalents 27,6% higher than the reference system, while the best can achieve 363% of GHG savings.

The results underlined also that the emissions of biogas systems generally creates higher impacts than the reference systems concerning the majority of the categories recommended by the ILCD (i.e. human toxicity, ecotoxicity, acidification). Preferring manure that avoids the emissions that otherwise the undigested material would cause resulted to be the best solution.

Keywords: Biogas, Anaerobic digestion, Upgrading, LCA, Renewable Energy Directive, ILCD, Digestate.

ANALISI DEL CICLO DI VITA DI SCENARI DI PRODUZIONE ED UTILIZZO DI BIOGAS NEL CONTESTO EUROPEO

Aumentare la percentuale di energia rinnovabile nei consumi europei è un punto chiave della politica dell'Unione Europea. Con la Direttiva 2009/28/EC sulle energie rinnovabili (Renewable Energy Directive, RED), la Commissione Europea ha sottolineato che l'uso di biomasse può fornire un contributo significativo alla riduzione delle emissioni di gas serra e una maggiore garanzia di autosufficienza energetica.

La digestione anaerobica è generalmente considerata una via sostenibile di impiego di biomasse per la produzione di un combustibile, il biogas, utilizzabile per generare elettricità o come sostituto del gas naturale. Essa, infatti, può evitare in modo significativo il rilascio di gas serra, poiché le emissioni di anidride carbonica biogenica che avvengono durante l'utilizzo del biogas corrispondono alla CO_2 che viene catturata dalla biomassa in fase di produzione.
Tuttavia, attualmente l'impatto sui cambiamenti climatici dovuto alla filiera di produzione ed utilizzo del biogas è fortemente influenzato da diversi fattori, come ad esempio la scelta del materiale da sottoporre a digestione anaerobica e la gestione dei residui del trattamento, responsabili soprattutto di emissioni di CO_2 fossile, metano e protossido di azoto in diverse quantità. La differenza in termini di emissioni di gas serra tra lo scenario migliore ed il peggiore può essere enorme e dovrebbe essere tenuta in considerazione nel formulare politiche volte a regolamentare il settore e a distribuire incentivi.

Lo scopo del lavoro è stata l'analisi delle emissioni di diverse filiere di produzione di energia da biogas con particolare attenzione per quelle criticità che sono state trascurate da altri studi e che si sospettava influenzassero il conteggio delle emissioni nell'ambiente, e quindi i relativi impatti.

Il primo punto cruciale della strategia energetica improntata sul biogas è la scelta della materia prima da destinarsi a digestione anaerobica. Liquami e reflui animali da zootecnia sono da tempo le biomasse più usate. La loro inevitabile produzione e gestione è responsabile di elevate emissioni di metano, protossido di azoto ed ammoniaca, che possono essere evitate se la biomassa viene stabilizzata anaerobicamente. Tuttavia, attualmente, le colture energetiche (mais, frumento, erba...) tendono ad essere prodotte ed utilizzate in quantità sempre più rilevante grazie al fatto che la loro maggiore efficienza e disponibilità possono garantire interessanti sussidi ai produttori.

In secondo luogo, il biogas prodotto può essere usato per ottenere sia elettricità in cogenerazione con calore, sia biometano da inserirsi nelle reti di gas naturale o da utilizzarsi quale carburante per veicoli, dopo la rimozione di tutti i componenti indesiderati (anidride carbonica, idrogeno solforato...) con tecnologie dette di upgrading. In particolare, ognuna di queste tecnologie è caratterizzata da una propria efficienza e da richieste di calore ed energia.

Inoltre, la digestione anaerobica produce un residuo chiamato digestato. Attualmente, molti dei piccoli impianti europei hanno una vasca aperta in cui il digestato viene immagazzinato in attesa della stagione primaverile durante la quale può essere sparso sui terreni agricoli ad apportare un interessante contributo in termini di sostanze nutrienti, anche se pochi dati sono disponibili per quanto riguarda la sua composizione. Tuttavia, la digestione anaerobica nella vasca continua spontaneamente liberando in atmosfera metano (CH_4), protossido di azoto (N_2O) e ammoniaca (NH_3). Se al contrario il digestato viene immagazzinato al chiuso, il biogas prodotto può essere ancora captato e i rilasci di N_2O e NH_3 evitati.

Addizionali emissioni di metano si possono riscontrare nei diversi processi componenti la filiera: perdite dal digestore, emissioni dal motore cogenerativo, percentuali nei flussi gassosi residui delle tecnologie di upgrading.

A tutto ciò si aggiunge che la sostenibilità non si può basare solo sulla valutazione dell'impatto sul cambiamento climatico causato dai gas serra, poiché la produzione e l'utilizzo del biogas sono responsabili di altre emissioni in atmosfera, nelle acque o al suolo aventi conseguenze sulla salute umana e degli ecosistemi. Per questo, lo studio è stato effettuato con una prospettiva di tipo Analisi del Ciclo di Vita (LCA, Life Cycle Assessment), seguendo le indicazioni dell'International Reference Life Cycle Data System (ILCD) Handbook pubblicato dalla Commissione Europea, al fine di considerate tutte le emissioni dalla culla (produzione delle colture energetiche) alla tomba (produzione finale di energia).

Lo studio è stato effettuato presso la Cleaner Energy Unit dell'Institute of Energy and Transport del Joint Research Centre con sede a Petten (NL). L'unità in questione è stata incaricata di quantificare le emissioni di gas serra da biomasse solide e gassose in occasione della pubblicazione del nuovo Impact Assessment che andrà ad aggiornare il SEC (2010) 65 ad integrare la Direttiva RED. I risultati del presente lavoro saranno indirizzati a valutare le debolezze della metodologia proposta dalla Commissione nel calcolo delle emissioni evitate di gas serra dalle filiere del biogas.

METODOLOGIA

Lo sforzo principale del lavoro è stata la modellazione di processi e scenari comprendenti tutti gli aspetti di recente interesse nel contesto europeo legate alla produzione e all'utilizzo del biogas che le Analisi del Ciclo di Vita esistenti in letteratura non consideravano nel loro complesso.

I dati per questa modellazione sono stati raccolti dalla letteratura internazionale o da database europei al fine di integrare e completare le informazioni prese da Ecoinvent 2.2 con l'inclusione di valori riguardanti le tecniche e le tecnologie più comunemente usate nel sistema biogas.

- Come biomasse da destinarsi a digestione anaerobica sono state analizzate due colture energetiche (gli insilati di mais e di erba) e i reflui zootecnici. Per ognuno di questi, specifici calcoli e ricerche in letteratura hanno permesso di stimare il tasso di produzione di biogas.
E' stato inoltre scelto di considerare in ingresso un mix composto per il 45% da insilato di mais e per il 55% da reflui animali al fine di studiare anche uno scenario di co-digestione in modo da garantire l'appropriato tenore di solidi volatili.

- La distanza media dal punto di produzione della biomassa al digestore è stata ipotizzata pari a 10 km per reflui animali e 50 km per le colture energetiche, e con questi valori è stata modellizzata la fase di trasporto.

- Elettricità e calore necessari al digestore sono stati calcolati come la media dei consumi energetici di impianti esistenti, diversificati a seconda del tipo di materiale digerito.
Perdite sistematiche di metano dal digestore sono state stimate pari allo 0,3% del totale prodotto.

- Il biogas prodotto è stato studiato in prima istanza per quanto riguarda l'utilizzo in un motore cogenerativo al fine di coprire il fabbisogno di energia del digestore e di inviare 1 MJ di elettricità in rete. Negli scenari di cogenerazione, quindi, 1 MJ_{el} in rete è stata fissata come unità funzionale alla quale tutte le emissioni e I flussi di material ed energia sono stati riferiti. Le emissioni del motore cogenerativo sono state modellizzate da dati di letteratura.

- Il secondo metodo di utilizzo di biogas comunemente impiegato è la combustione in caldaia del biometano ricavato dopo una fase preliminare di purificazione (upgrading) del biogas e la sua alimentazione alle reti di distribuzione di gas naturale. Sono state analizzate quattro diverse tecnologie di upgrading, dfferenti per efficienza di captazione del metano e per richieste di elettricità e calore. Da dati di letteratura sono stati calcolati i seguenti inputs e outputs del processo di upgrading:

Tecnologia di Upgrading: inputs	**Elettricità** $\left[\frac{MJ}{Nm^3_{biometano}}\right]$	**Calore** $\left[\frac{MJ}{Nm^3_{biometano}}\right]$	**Biogas** $\left[\frac{Nm^3_{biogas}}{Nm^3_{biometano}}\right]$
Adsorbimento (PSA)	2,11	0	1,84
Assorbimento con acqua	1,69	0	1,78
Assorbimento fisico	1,79	1,10	1,80
Assorbimento chimico	0,79	2,88	1,75

Tecnologia di Upgrading: emissioni	**Perdite di CH_4** $\left[\frac{g}{Nm^3_{biometano}}\right]$
Adsorbimento (PSA)	36,2
Assorbimento con acqua	14,0
Assorbimento fisico	21,3
Assorbimento chimico	0,70

Unità funzionale di questo gruppo di scenari è 1 MJ di calore prodotto.

- In seguito, attenzione è stata posta nello studio dettagliato del contenuto di nutrienti nel digestato, che è utilizzato comunemente come sostituto dei fertilizzanti chimici e per tale motivo sparso sul suolo agricolo. Poiché non ci sono dati disponibili sulla composizione di digestato proveniente da specifiche tipologie di colture trattate anaerobicamente, il contenuto del digestato è stato calcolato considerando i nutrienti della biomassa grezza. Questi dati sono importanti per due ragioni: in primis, per poter calcolare la potenziale sostituzione dei fertilizzanti chimici e in secondo luogo perché il digestato emette in atmosfera CH_4, N_2O e NH_3 in funzione della sua composizione.

- Lo stoccaggio del digestato è stato analizzato sia in configurazione chiusa sia aperta. In tali vasche di accumulo, la digestione anaerobica continua incontrollata portando alla formazione di biogas. Con la prima configurazione, il biogas aggiuntivo può essere raccolto in modo da aumentare il rendimento di produzione di tutta la filiera, mentre nel secondo caso viene rilasciato in atmosfera, insieme a N_2O e NH_3. Entrambe le tipologie di scenario sono state analizzate e i dati calcolati sulla base della composizione del digestato ricavata, come illustra la seguente tabella:

Emissioni dallo stoccaggio del digestato	**CH_4 vasca aperta** $\left[\frac{g}{kg_{digestato}}\right]$	**NH_3 vasca aperta** $\left[\frac{g}{kg_{digestato}}\right]$	**N_2O vasca aperta** $\left[\frac{g}{kg_{digestato}}\right]$	**Biogas recuperato, vasca chiusa** $\left[\frac{dm^3}{kg_{digestato}}\right]$
Insilato di mais	0,593	0,0209	0,0083	1,615
Insilato di erba	0,593	0,0482	0,0190	1,615
Reflui zootecnici	1,02	0,2293	0,0906	1,948

- Il digestato è stato quindi trasportato, per ipotesi, per lo stesso numero di chilometri del materiale in ingresso all'impianto, e infine sparso su suolo agricolo, generando emissioni di CH_4, N_2O e NH_3 ma evitando l'uso di una certa percentuale di fertilizzante chimico. Entrambe i contributi sono stati analizzati: il processo di coltivazione delle colture energetiche è stato modificato diminuendo la produzione di fertilizzante chimico e in aggiunta le emissioni dovute allo spandimento sono state introdotte.
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	N-Fertilizzante chimico [% del fabbisogno totale della coltura]	**K-Fertilizzante chimico [% del fabbisogno totale della coltura]**	**P-Fertilizzante chimico [% del fabbisogno totale della coltura]**
Insilato di mais	12,67	28,05	- 26,65
Insilato di erba	89,33	Non richiesto	Non richiesto

Emissioni dallo spandimento di digestato	**CH_4** $\left[\frac{kg}{kg_{digestato}}\right]$	**NH_3** $\left[\frac{kg}{kg_{digestato}}\right]$	**N_2O** $\left[\frac{kg}{kg_{digestato}}\right]$
Insilato di mais	0,0000004	0,0000462	0,0000006
Insilato di erba	0,0000010	0,0001063	0,0000013
Reflui zootecnici	0,0000046	0,0005059	0,0000062

- Per quanto riguarda i reflui zootecnici, le emissioni di CH_4, N_2O e NH_3 che la gestione del materiale grezzo avrebbe causato se non fosse stato destinato a digestione anaerobica sono state ricercate in letteratura. Queste emissioni, da stoccaggio e da spandimento, sono state quindi sottratte agli scenari di produzione di biogas da reflui. Si tratta di contributi chiamati *crediti*.

Emissioni da reflui zootecnici non trattati	**CH_4** $\left[\frac{g}{kg_{reflui}}\right]$	**NH_3** $\left[\frac{g}{kg_{reflui}}\right]$	**N_2O** $\left[\frac{g}{kg_{reflui}}\right]$
Stoccaggio	3,1010	0,1511	0,0765
Spandimento	0,0038	0,5439	0,0111

- La produzione di 1 MJ di calore è stata comparata alla produzione dello stesso quantitative di calore ottenuto con la stessa caldaia di piccola potenza alimentata a gas naturale, come modellizzata dal database Ecoinvent 2.2

- Come sistema di riferimento per la produzione di 1 MJ di elettricità è stato considerato il mix europeo riportato in Ecoinvent 2.2.

Nella fase successiva, con il supporto del software GaBi per LCA, ogni processo è stato collegato per calcolare bilanci di massa ed energia in modo da avere come risultato le emissioni prodotte e le risorse consumate nell'intero ciclo di vita.

L'ultima parte del lavoro è stata l'analisi critica dei risultati che sono stati ottenuti raggruppando le emissioni e i consumi di risorse in categorie di impatto ed esprimendole omogeneamente mediante dei fattori implementati nei diversi metodi di caratterizzazione. I metodi e le categorie di impatto sono stati scelti tra i raccomandati dall'ILCD nella recente pubblicazione *Recommendations for Life Cycle Impact Assessment in the European context* (Novembre 2011) e per la prima volta applicati ad un'analisi sulle filiere del biogas.

RISULTATI

Lo studio ha dimostrato che nonostante le politiche ambientali incoraggino la produzione e l'utilizzo di biogas come fonte energetica in grado di evitare emissioni di gas serra, in realtà negli impianti reali diverse tecniche impiegate causano emissioni di gas più alte del sistema di riferimento scelto.

▪ Lo studio ha confermato che emissioni evitate di gas serra (GHG) rispetto ai sistemi energetici di riferimento (il mix di elettricità europea per le filiere con cogenerazione e la combustione di gas naturale in caso di upgrading) si possono trovare in ogni scenario in cui il digestato è mantenuto al chiuso prima dello spandimento e nel quale l'addizionale quantità di biogas prodotto viene recuperato. I risparmi rispetto al sistema di riferimento sono i seguenti:

- In scenari di cogenerazione (CHP):14,2% per insilato di erba, 33,8% per insilato di mais, 100,6% per co-digestione, 363% per reflui zootecnici.
- In scenari di upgrading, i risultati sono riportati in Figura 1, in cui è possibile vedere il contributo delle diverse tecnologie.

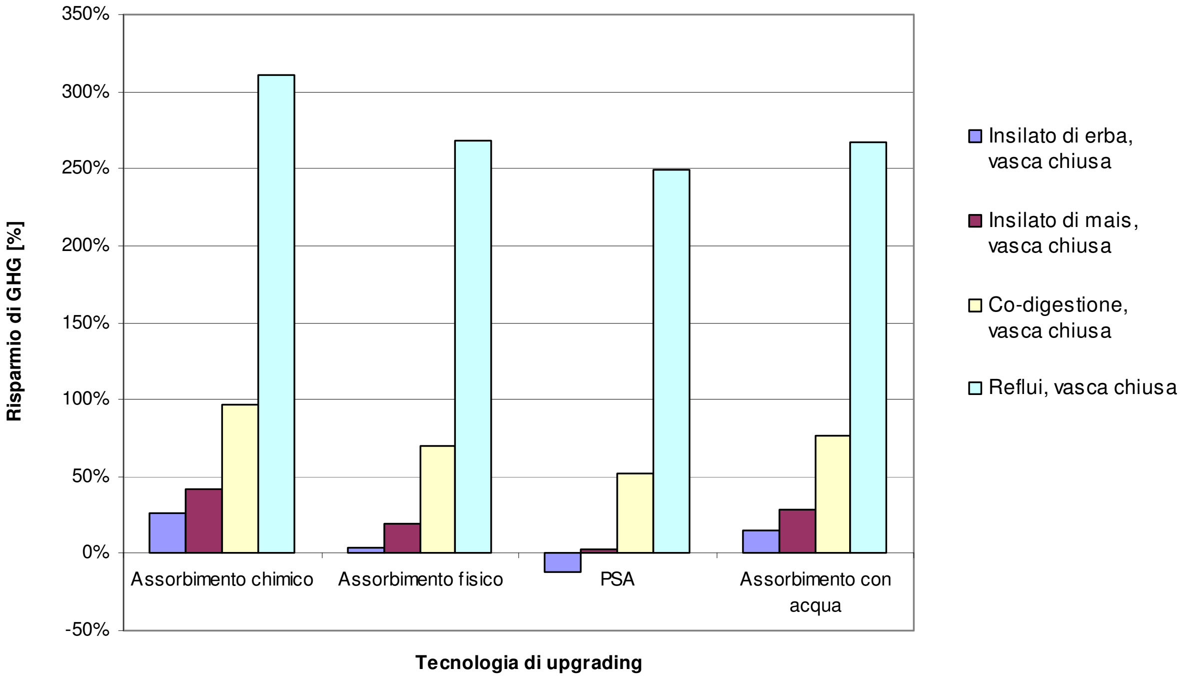

Figura 1 – Emissioni evitate di GHG per diverse biomasse nella filiera di produzione di biogas con upgrading e utilizzo di biometano, valori calcolati rispetto alla produzione di 1 MJ di calore da gas naturale

▪ Se la vasca è aperta, questi benefici vengono persi e l'impatto sulle emissioni di gas serra risulta maggiore del sistema di riferimento per le elevate emissioni di metano e protossido di azoto. Solo gli scenari che prevedono la digestione dei reflui zootecnici, sia trattati da soli che in co-digestione con insilato di mais, sono sostenibili da questo punto di vista grazie all'assegnazione dei crediti. I risparmi sono i seguenti: -27,6% per insilato di erba, -3,6% per insilato di mais, 45,3% in co-digestione, 242,3% per i reflui.

- La Figura 1 mostra che il divario tra le diverse tecnologie di upgrading dipende dalle perdite di metano: più alti sono i rilasci di CH_4, più alte sono le emissioni di gas serra. Perciò, l'assorbimento chimico dovrebbe essere preferito perché perde soltanto lo 0,1% del metano prodotto, seguito dall'assorbimento con acqua (2%), l'assorbimento fisico (3%) e l'adsorbimento PSA (5%). E' quindi essenziale specificare a quale tipo di tecnologia si fa riferimento, come questa LCA fa per la prima volta, dato che l'impatto sul cambiamento può essere fortemente influenzato dalle percentuali di CH_4 nei gas di scarto. Se viene usata la tecnica di gestione del digestato più appropriata, la sostenibilità rispetto alle emissioni di gas serra è raggiunta anche se le perdite di metano dalle tecnologie di upgrading eccedono i valori garantiti dai costruttori. Si raccomanda però di assicurare che questi rilasci non superino il 5,5% del metano prodotto, come è stato visto possibile da misurazioni in impianti reali [41]. Notevoli benefici si possono visualizzare se il gas di scarto delle tecnologie di upgrading viene bruciato in torcia al fine di convertire il CH_4 in CO_2 biogenica.

- Le incertezze dovute al calcolo delle emissioni di N_2O dal digestato possono portare a sovrastimare o sottostimare le emissioni di GHG dello scenario. In letteratura, non è stata trovata concordanza tra i fattori di emissione di N_2O da digestato: il range di valori trovati va da 0,000120 $kgN_2O/kg_{digestato}$ [17] a 0,0000346 $kgN_2O/kg_{digestato}$ [20].

Il presente studio ha messo in luce anche i potenziali impatti riguardo altri problemi ambientali. I risultati sottolineano come uno scenario con un effetto positivo in termini di risparmio di emissioni di gas serra può causare altri problemi ambientali.

- Scenari di produzione e utilizzo di biogas in cui le colture energetiche sono digerite anaerobicamente hanno performance peggiori rispetto al sistema di riferimento scelto per quanto riguarda la tossicità umana, la formazione di particolato, la formazione di ozono fotochimico, l'acidificazione, l'eutrofizzazione, l'ecotossicità e il consumo di risorse. Le cause principali sono da ricercarsi nei processi di coltivazione, nelle emissioni del motore cogenerativo e nella filiera di produzione dell'energia elettrica della rete, quando previsti.

- Piccoli benefici si possono trovare in tutti gli scenari CHP soltanto riguardo all' emissione di sostanze lesive dell'ozono stratosferico (tra -2% delle emissioni nel caso di mais con vasca aperta e -43% per i reflui), mentre la produzione di radiazioni ionizzanti è più bassa del 95% perché il sistema di riferimento considera anche la quota parte di energia nucleare nel mix europeo. Negli scenari di upgrading, solo la deplezione dell'ozono stratosferico ha emissioni più basse del sistema di riferimento, tra l'83% e il 92% in meno.

- I reflui zootecnici sono il tipo di biomassa più idoneo perché non richiedono un processo di coltivazione, ma i risultati non possono prescindere dal conteggio dei crediti che tengono in considerazione le emissioni evitate legate al trattamento alternativo della biomassa stessa comprendente ad esempio lo stoccaggio e lo spandimento del materiale non stabilizzato. Oltre a garantire i più alti risparmi di gas serra, gli impatti restano inferiori a quelli dello scenario di riferimento per quanto riguarda:
    - In scenari CHP: formazione di materiale particolato (-26%), l'ecotossicità terrestre, (-52%), l'eutrofizzazione (-128%) e l'acidificazione (-137%)
    - In scenari di upgrading con il digestato immagazzinato al chiuso: eutrofizzazione marina (range da -119% a -143%, in dipendenza dal tipo di tecnologia), formazione di ozono fotochimico ([-46%;-76%)]), formazione di particolato ([-498%;-560%]) e acidificazione ([-677%;-731%]).

- La produzione delle colture energetiche è il processo più impattante (ad esempio, per l'ecotossicità, l'eutrofizzazione e l'acidificazione). Perciò, limitare l'intensità della coltivazione e preferire l'impiego di residui potrebbe produrre evidenti benefici. Più bassa è la pressione agricola nella produzione della biomassa, minori sono le emissioni di GHG, a causa della produzione e dell'utilizzo dei macchinari, dei fertilizzanti e dei pesticidi. Dato che per l'erba il tasso di produzione di biomassa per ettaro (29,1 t/ha) è più basso rispetto al mais (42,5 t/ha), le pratiche agricole sono più impattanti.

- Poche differenze appaiono tra le tecnologie di upgrading nella maggioranza delle categorie di impatto. Quando la coltivazione è il processo più impattante (come per l'acidificazione, la formazione di particolato, l'eutrofizzazione), gli scenari prevedenti l'utilizzo dell'assorbimento chimico causano emissioni più alte perché più biomassa in ingresso è richiesta per raggiungere alla produzione di 1 MJ di calore, essendo che questa tecnologia usa energia termica fornita dalla combustione di biogas stesso. Al contrario, grazie alla bassa necessità di energia elettrica, l'assorbimento chimico è la soluzione migliore se l'elettricità presa dalla rete è la principale fonte di emissioni (ad esempio, per la radiazione ionizzante).

- L'impiego di biogas in motori cogenerativi è risultata essere la soluzione più opportuna perché un minor numero di categorie hanno impatti più alti rispetto al sistema di riferimento. E' da tenere presente però che le più elevate emissioni dovute alla produzione di elettricità da mix europeo includono anche fonti quali il nucleare, il carbone e la lignite, dall'alto potenziale radioattivo.

- Al contrario, il biometano viene confrontato con il gas naturale, che è uno tra i combustibili fossili più puliti. Il fatto che produzione e utilizzo di biometano siano più impattanti è dovuto anche a questo.

- Il confronto tra i risultati della presente Analisi del Ciclo di Vita e i valori tipici e standard di emissione di GHG per la produzione di biogas riportati nel COM(2010)11 che integra la Renewable Energy Directive (RED 2009/28/EC) hanno sottolineato che la procedura della Direttiva trascura importanti questioni quali:
    - i valori di GWP_{100} del report più recente dell'IPCC;
    - le differenze tra lo stoccaggio del digestato all'aperto o al chiuso;
    - la produzione di macchinari;
    - i crediti per i reflui zootecnici, ovvero le emissioni evitate dovute allo spandimento e allo stoccaggio del refluo grezzo;
    - le perdite di metano nei dispositivi usati per produrre l'energia finale;
    - nuove biomasse emergenti, come le colture erbacee, e la co-digestione.

E' quindi auspicabile che l'eventuale aggiornamento dei valori consideri questi temi. Infatti, secondo i risultati di questa LCA, sono idonei all'essere conteggiati nelle politiche ambientali degli Stati Membri soltanto gli scenari in cui i reflui sono tra le biomasse in digestione, poiché sono i soli che superano la soglia del 35% delle emissioni evitate.

1
INTRODUCTION

Increasing the share of renewable energy in total EU energy consumption is a key policy objective in the European Union. With the Renewable Energy Directive 2009/28/EC (RED), the EU Parliament states that the use of biofuels offers significant opportunities for Europe to reduce greenhouse gas emissions and improve the security of its energy supply.

Biogas production is generally considered a very sustainable way to produce a fuel used for electricity generation or as substitute for natural gas. In fact, high greenhouse gas savings can be guaranteed since biogas utilisation cause biogenic carbon dioxide emissions that correspond to the CO_2 intake during the biomass production.

However, the actual impact on climate change due to biogas is strongly influenced by many factors, such as the choice of feedstock and the management of the residues, which are responsible for variable methane, nitrous oxide or fossil CO_2 emissions. The difference in terms of greenhouse gas savings between the best and the worst case can be huge and should be kept in high regard when formulating policies regulating the sector or providing subsidies.

The first critical point is the choice of the feedstocks. Manure and animal residues have been historically the main feedstocks for biogas production. Since animal manures are one of first source of CH_4, N_2O and NH_3 in the agricultural sector, the anaerobic digestion allows avoiding the emissions that would occur in the management of the raw material.

However, with the growing interest in biogas and the generous subsidies granted for biogas electricity, producers have started to cultivate and use more and more of the so-called energy crops (maize, wheat, grasses,…) that can enable larger production capacities.

Secondly, the biogas produced can be utilised in different configurations: it is used to obtain electricity via a combined heat and power engine (CHP), or it is upgraded by removing carbon dioxide and other undesired compounds to allow its injection into the natural gas grid or its use as vehicle fuel. Each technology has its own efficiency and typical emissions.

Thirdly, anaerobic digestion generates a residue called digestate. One of the most important steps in the biogas production and utilisation pathway is its management: currently, many of the existing small-scale biogas plants tend to have an open tank where the digestate is collected after the digestion and stored before it is re-applied on the fields as fertiliser, during the spring, because of its high nutrient content. However, digestion continues also during storage and significant emissions of CH_4, N_2O and NH_3 can occur. On the contrary, if the

digestate is stored in a closed container, the methane produced can be collected and the N_2O and NH_3 emissions can be avoided.
Furthermore, CH_4 leakages can occur from the digester, from the CHP engine and from each upgrading technology (in different percentages).

Final evaluation of sustainability can not be based only on the impact on climate change since biogas production and utilisation is responsible for several emissions to soil, air and water that can have consequences on human and ecosystem health. Since it is able to go deeper into all these impacts, Life Cycle Assessment is a complete and suitable analysis.

The aim of this study is to inspect the emissions of different production and utilisation chains of biogas with a Life Cycle Assessment (LCA) perspective, focusing on those criticalities that are suspected to influence the emissions and the consequent impacts and that other LCA studies did not fully consider. Most of the data used in this LCA to model new issues are found in literature or adjusted to refer to the specific case studied, while values for the reference systems and the traditional processes are taken from existing databases (mainly Ecoinvent 2.2) after a critical analysis.

This study is performed in support of the work of the Cleaner Energy Unit (CEU) of the Institute of Energy and Transport (IET) that is part of the Joint Research Centre (JRC) of the European Commission.
CEU is in charge for the calculation of the GHG emissions from solid and gaseous biomass to be published with the new Impact Assessment that has to update the SEC(2010) 65 in integrating the RED.
The results of this study are also compared to the values indicated by the European Commission in previously published documents and this will help to underline the strengths and weaknesses of the RED methodology.

This thesis is structured as follows:
Chapter 1 introduces the literary review on LCA analysis or environmental studies about biogas systems. Then, the innovations introduced by this work are enounced.

In Chapter 2, the Life Cycle Assessment methodology, as recommended in European Commission ILCD [31], is explained.

In Chapter 3, the biogas production and end use are explained by introducing the most frequently used techniques and technologies in Europe, concerning the feedstocks, the pre-treatments, the digestion process, digestate management and biogas utilisation. Finally, an overview of the EU context for the future perspectives is added.

In Chapter 4, the steps of an LCA analysis are applied to biogas production and utilisation.
The goal and the scope are defined (Paragraph 4.1) and so is the selection of the pathways to be analysed, the most important issues and assumption and the collection of the data are reported and explained.
The description of the processes (Paragraph 4.2) includes the selection and the explanation of the phases included in a generic biogas pathway: cultivation, transport, anaerobic digestion, digestate management, CHP or upgrading, provision of heat and electricity. In addition, the reference system is characterised.
Life Cycle Inventory (4.3) represents each pathway in a detailed way. A model of the system under analysis (foreground) is built and with the help of a LCA software (GaBi) all the elementary flows between the foreground system and the environment (background system) are identified and quantified.
Life Cycle Impact Assessment and Interpretation (4.4) reports, for the impact categories chosen, the methods used to calculate the results. Each impact category is analysed and commented for the most representative pathways under analysis.
The LCA ends its sequence of steps with a sensitivity analysis (4.5) that demonstrates how a variation of the most sensitive assumptions could affect the final results. The study focuses on these topics: the fertilising power of the digestate, the utilisation of residual grass, the inclusion of manure credits, N_2O emissions from manure, methane leakages and the treatment of the off-gas in upgrading, and finally the self-sufficiency of the plant in terms of heat and electricity.

In Chapter 5, the attention is focused on the Renewable Energy Directive and the methodology to calculate the GHG performance of biogas pathways as expressed in the related Report COM(2010) 11. The differences between this method and a full LCA approach are underlined.

Since LCA is an iterative approach, a final chapter of conclusions reports the most interesting results identified by this work and underlines the difficulties and the gaps that could be fulfilled with the continuation of this work.

1.1 PREVIOUS STUDIES ON LCA AND BIOGAS PATHWAYS

A large number of studies were conducted on the environmental impact of biogas production, focusing particularly on the energy balance and the greenhouse gas (GHG) emissions.

Poschl et al. [60] evaluated the impact of different feedstocks, single or co-digested, and process chains (production, conversion and utilisation) on the energy balance of biogas systems. The balance was calculated as Primary Energy Input to Output ratio (PEIO). The input data was derived from biogas systems and technologies existing in Germany. The best performing scenarios resulted to be the following ones: for farm-scale plant, a CHP with full heat utilisation; for large-scale plant, upgrading to biomethane. In both of them a close tank for digestate was highly recommended.

Elsgaard [27] analysed the GHG emissions from the cultivation only of energy crops (winter wheat and rapeseed) for bioliquids and biogas production. The aim was to compare the default value of GHG emissions from cultivation contained in the EU Directive 2009/28/EC Annex V with the amounts obtained with calculations for Denmark, considering different scenario based on the utilisation of chemical fertilisers, animal manure or digestate. The results in terms of GHG savings were generally equal or lower than the corresponding emissions indicated in the Annex V. However the sensitivity analysis showed that many uncertainties of the approach of the calculation of N_2O emissions could lead to different results.

Some of these studies refer to manure and energy crops. However, different assumptions, methodologies, system boundaries and functional units make these studies difficult to compare.

Gerin et al [38] analysed maize and grass as feedstocks and the agricultural options that could be most relevant for southern Belgium and the surrounding areas. The results led to determine the balance of energy and CO_2 emissions for each option. The study concluded that both maize and grass allow the same CO_2 emission savings and thus are both suitable for biogas production. However, maize appeared to have a higher yield per hectare but grass could be grown in areas in which maize cultivation is not feasible. From the energy point of view, farm scale plants are recommended because they need less diesel fuel for transport, but further economical analysis is required to establish the effective economical and technical sustainability. The study considered only the emissions linked with fuel and fertilisers utilisation during the biogas production and utilisation in CHP devices, while emissions from digestate and leakages were neglected.

Woess-Gallasch et al. [75] analysed an existing biogas plant in Austria, under different conditions of digestate storage, to quantify the GHG emissions with an LCA approach. In the plant, maize and manure were co-digested. This study states that open storage of digestate causes emissions 29% higher than closed storage, which avoids 44% GHG compared to the reference system that refers to the spreading of undigested manure and the use of electricity from natural gas. This study considered the leakages of methane during both combustion of biogas (data from literature) and storage of digestate (measurements), but N_2O losses due to the digestate management were neglected. In addition, land use change data were added.

Thyø [71], evaluated the GHG emissions and resource consumption, considering biogas made from whole-crop maize (silage) used both for heat & power and upgraded, compressed and used for transport. The same evaluations were made for biogas from manure. Different assumptions for digestate emissions were considered, for example maize digestate was assumed to emit the same amount of CH_4 and N_2O as mineral fertiliser. The study also compared the environmental impacts of making biogas with the alternative use of the substrate (with the production of a different feedstock for biodiesel, bioethanol or power and heath production). The study referred to the situation of northern Germany and Denmark and considered a particular technology of biogas production. The results indicated that the digestion of manure reduced GHG emissions and that both CHP from biogas from maize and willow combustion are suitable alternative. Finally, bioliquids appeared to be a less sustainable option.

Adelt et al. [1] studied the GHG emissions and Cumulative Energy Demand balance of an existing plant digesting maize and considering in addition an upgrading phase with a PSA technology. This resulted in a positive reduction of emissions and, as already seen, in a perspective of better results using high efficiency and controlled technologies. The assumption of a higher amount of chemical fertiliser avoided due to digestate spreading was linked to high GHG reduction. No emissions during the upgrading step were added.

Kimming et al. [47] compared the production of biogas from ley crops with willow cultivation and combustion and with reference system. Farm-scale applications and different technologies of end utilisation were considered. The most interesting scenario included the recovery of straw and ley, the spreading of digestate and biogas utilisation in a small CHP.

With regards to multiple impact categories, numerous LCA studies were conducted. Many of these studies compare alternative scenarios of utilisation of the biomass.

Jury et al. [45] calculated the environmental burdens of monofermentation of a generic group of energy crops at pilot scale, and the following injection of methane into the grid, without considering the utilisation phase. The study demonstrated that biogas could give higher impacts to human health and ecosystem quality than natural gas and lower impacts to climate change and resource consumption. The upgrading technology considered was water scrubbing but the leakage of methane was assumed to be 1%. This value is far from the average in literature but it is more likely to apply for future technology improvements.

Schumacher et al. [65] performed an LCA comparing the production of biogas and biogas+bioethanol from maize and triticale grains. Only few impact categories were considered. Data were taken from the database implemented into the GaBi Software and from laboratory tests, referring to German context. It was showed that the energy output/input ratio was higher for biogas production with digestate utilisation than for bioethanol extraction. In addition, whole crop use saved more GHG than the digestion of the grain only.

Siegl et al. [67] illustrated the contribution that different processes in a biogas system gave to create impacts on the environment. Input basic data were taken from the Ecoinvent database, while specific values were calculated or collected from 34 existing plants in Austria, aggregated by plant size. These are the resulting impacts on different categories:

- GWP_{100}: 75% of emissions resulted to be due to operation and digestate management (CH_4 emission from CHP and digestate storage, N_2O emissions from digestate storage and spreading);
- Acidification and Eutrophication Potential: NH_3 emissions from digestate management resulted to be responsible for 67-90% of the total impact; the second contribution was NO_x-emission from the CHP engine;
- Photochemical Ozone Creation Potential: emissions were higher than credits given for the reference system. CO and CH_4 emissions from the CHP were the main sources;
- Abiotic and Ozone Depletion Potential: critical stages were cultivation and transport;
- Land Use Change: the highest contribution came from the cultivation and digestate management;
- Toxicity potentials: depended on cultivation and transport.

Borjesson and Berglund [7, 8, 11, 12] gave the most complete overview of the biogas system referring on different raw materials and considering both energy balance and environmental impacts. However, the main thesis of the study was the uncertain sustainability of the process due to different goals and methods with which to refer the processes. For example, if the purpose is to obtain ah high heat amount, it is better to cultivate the area with willow for direct combustion than using biogas. On the contrary, if the production of digestate as fertiliser is considered, biogas pathways can be judged as sustainable.

Poeschl et al. [59] compared multiple biogas production and utilisation pathways in order to identify areas where further mitigation of potential environmental impacts could be realised. The study firstly attempted to focus also on digestate processing and handling unit processes. The results showed that straw and maize silage digestion caused lower impacts than grass and wheat utilisation, while in order to maximise the environmental impacts mitigation, a higher proportion of agricultural residues and organic waste streams should be included in co-digestion. Recovery of residual biogas from the digestate storage areas was

the key determinant of the performance of digestate processing and handling. The main factor was in the reduced biogas leakage to the atmosphere.
However, no specific data on manure management or the analysis of different upgrading technologies were included.

As far as utilisation of biogas is concerned, Chevalier et al. [18] compared the CHP technologies for co- and tri-generation. Since biogas from energy crops saves GHG emissions, also the high eutrophication and acidification potential could be reduced with high efficient plants with dispositive that avoids NO_x emissions.
BIOGASMAX project [9] adopted the well-to-wheel approach, considering the entire chain of biomethane from waste collection to use in vehicles, recovery of organic matter in agriculture and the essential steps of upgrading, distributing and transporting biomethane. The aim was to support the utilisation of biomethane as a vehicle fuel. The case of different European cities was analysed. The main conclusion was that no combination of feedstocks or production and upgrading technology causes the least impact across all categories.

1.1.1 Open issues and scope of this work

- A comprehensive study analysing the most used feedstocks and technologies of biogas systems in Europe with a real and complete LCA approach, following the indication of the ILCD, is missing in literature. In particular, it is the first work on biogas that selects the characterisation methods to calculate the environmental impacts among the recommended in the ILCD *Recommendations for Life Cycle Impact Assessment in the European context*, published in November 2011. In this study, it will be also showed how the choice of different methods referring to the same impact can affect the results. For this reason, if internationally recognised rules are followed in choosing the methods, the results are more objective.

- The upgrading phase is never analysed comparing different technologies and thus considering various methane leakages and energy consumptions. When upgrading is considered in LCA studies, it is done by accounting a generic percentage of methane leakage pretending to represent the average of the technologies. In addition, specific pre-defined processes or inventories of the upgrading of the biogas are not implemented in the databases used for LCA. Thus in this study four upgrading technologies are introduced: data are collected in literature and processes are modelled. The aim is to quantify their different environmental performances.

- Any LCA analysed in details the digestate management with the attempt to consider the recirculation of nutrients. In fact, digestate composition, linked to the raw material composition, affects its fertilising power and the emissions of gases in the environment. In this study, the balance of the nutrient is considered.

- Credits for the avoided emissions of CH_4, NH_3 and N_2O from untreated manure storage and field application are taken into account. The account of the credits consists in assuming that the anaerobic digestion avoids the emissions that would occur in the management of the raw material.

- Finally, the work has the intent to compare the results found with a LCA approach with the default and typical values of greenhouse gas emissions included in the *Report COM(2010) 11 on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling* calculated according to the methodology reported in the Annex V of the RED.

2

LIFE CYCLE ASSESSMENT (LCA)

“a process of compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”

ILCD Handbook, 2010 [31]

Life Cycle Assessment is a scientific, structured and comprehensive method, internationally standardised in ISO 14040:2006 (Principles and framework) and 14044:2006 (Requirements and guidelines). It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any specific good or service. Importantly, it allows for direct comparisons, based on the quantitative functional performance of the analysed alternatives.

The ISO 14040 and 14044 standards provide the indispensable framework for Life Cycle Assessment. This framework, however, leaves the individual practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance. The International Reference Life Cycle Data System (ILCD) has therefore been developed to provide guidance for consistent and quality assured Life Cycle Assessment data and studies [31].

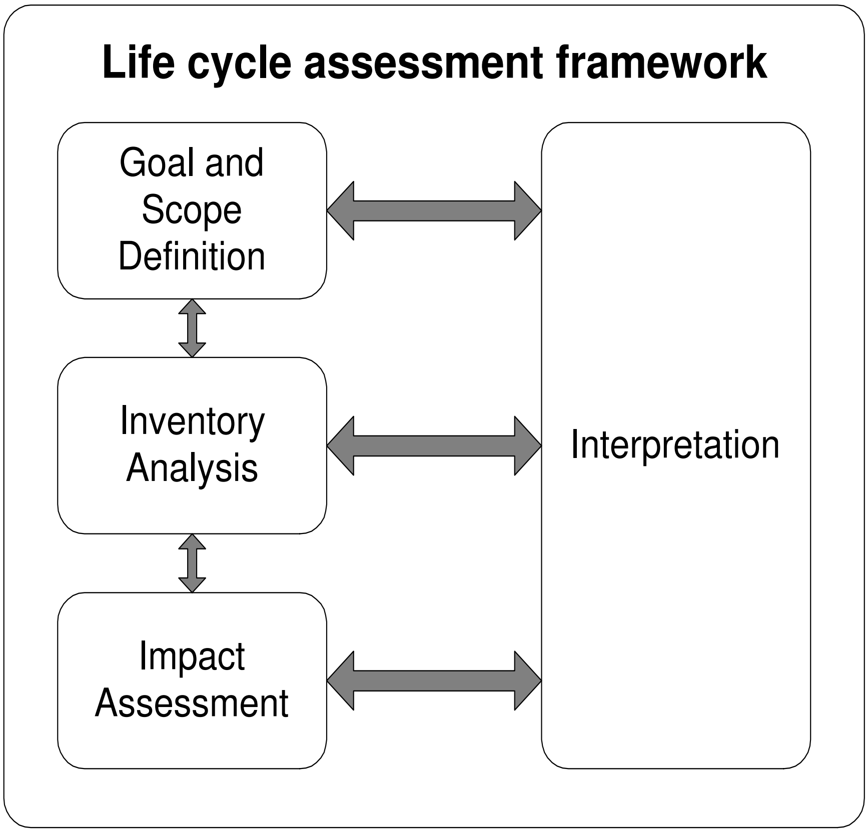

Figure 1 – Life Cycle Assessment framework [31]

The process of a LCA study is an iterative act. There is a sequence of steps, but there is always the possibility of returning to an earlier step and changing parameters or adding information if required. Even if the impact assessment is completed, it is mandatory to go back to the goal and scope definition in order to verify that the results fulfil the requirements of the goal definition and whether any correction of the scope is needed. Finally, the LCA study is repeated several times until the goal of the study is reached (see Figure 1).

In this Chapter, the four main steps of a Life Cycle Assessment are detailed: Definition of goal and scope (2.1), Life Cycle Inventory (2.2), Life Cycle Impact Assessment (2.3), Life Cycle Interpretation (2.4).

In the last paragraph (2.5), the software used to perform the LCA of this study is briefly introduced.

2.1 DEFINITION OF GOAL AND SCOPE

In this phase, the goal of the study and the reference function and flows are defined. The boundaries have to be thoroughly defined and must be consistent with the intended application. Additionally, the system under investigation must be defined and described, and also the time and the place in which the investigation takes place.

Data quality is defined by time, place, technology, and registration method, for example measured data or calculated data. Finally, impact categories and impact assessment methods are stated. With these definitions complete, the frame of a LCA study is made.

2.1.1 Definition of goal: identifying purpose and target audience

Life Cycle Assessment starts with the definition of the goal of the study. Six aspects shall be addressed and documented [31]:

- Intended application(s) of the deliverables / results
- Limitations due to the method, assumptions, and impact coverage
- Reasons for carrying out the study and decision-context
- Target audience of the deliverables / results
- Comparative studies to be disclosed to the public
- Commissioner of the study and other influential actors

In addition, the definition of the decision situations has to be taken. Three options are possible, as defined in the ILCD Handbook [31]:

- A: Micro-level, product or process-related decision support studies
- B: Meso-level and macro-level, strategic ("policy") decision support studies
- C: Monitoring studies

2.1.2 Definition of scope: what to analyse and how

At this point, the following aspects have to be defined. To understand each step, some definitions are added [31].

- The system or process that is studied and its functions, functional unit, and reference flows

An LCA is always based on a precise, quantitative description of the **function(s)** provided by the analysed system. This is generally done by using the **functional unit** that names and quantifies the qualitative and quantitative aspects of the function(s) along the questions "what", "how much", "how well", and "for how long". The *qualitative* definition of the system's function(s) is a description of the way in which the function(s) are provided and of other qualities of the product. These qualitative aspects include those that are not easily quantifiable because they are related e.g. to the user's perception. Perception aspects can be e.g. being fashionable or possessing specific design-features such as shape, touch, etc. The *quantitative* definition of a product's functional unit should refer to technical standards wherever possible and appropriate.

The **reference flow**, finally, is the flow (or flows in case of multifunctional processes) to which all other input and output flows refers.

- System boundaries

The **system boundaries** define which parts of the life cycle and which processes belong to the analysed system. They hence separate the analysed system from the rest of the technosphere.

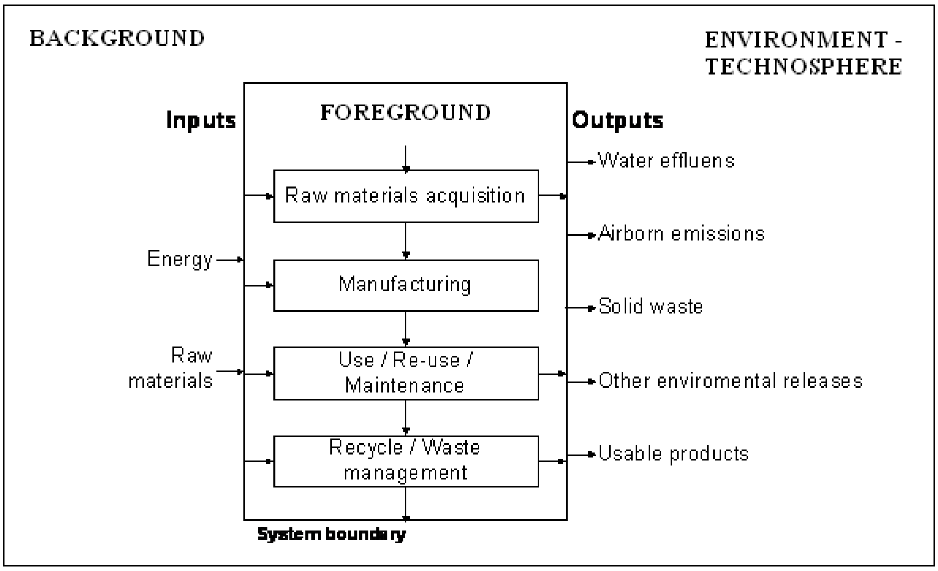

Figure 2 - System boundaries

There are four main options to define the system boundaries used [37]. Figure 3 helps to understand the differences.

- **Cradle to Grave:** includes the material and energy production chain and all processes from the raw material extraction through the production, transportation and use phase up to the product's end of life treatment.

- **Cradle to Gate:** includes all processes from the raw material extraction through the production phase (gate of the factory); used to determine the environmental impact of the production of a product.

- **Gate to Grave:** includes the processes from the use and end-of-life phases (everything post production); used to determine the environmental impacts of a product once it leaves the factory.
- **Gate to Gate:** includes the processes from the production phase only; used to determine the environmental impacts of a single production step or process.

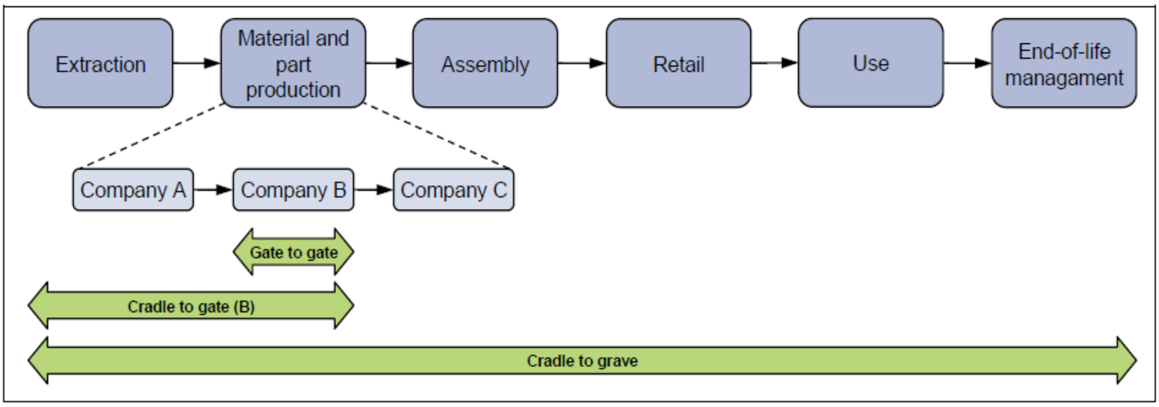

Figure 3 – Options to define system boundaries [37]

In general, all processes and flows that are attributable to the analysed system have to be included in the system boundaries. However, not all these processes and elementary flows are quantitatively relevant: the irrelevant ones can be entirely cut-off and the effort that would otherwise be needed to collect the data can be used to focus on obtaining better data for the relevant processes and elementary flows. **Cut-offs** are quantified in relation to the percentage of environmental impacts that is approximated to be excluded via the cut-off (e.g. "95%" relates to cutting off about 5% of the total environmental impact (or of a selected impact category). Obviously it requires an approximation to know what the 100% impact is, because if one would know the total impact exactly, there would be no need for a cut-off. But the total inventory is always unknown for all life cycle approaches - the 100% always need more or less approximation and extrapolation from the measured or calculated data. For LCI data sets, the cut-off is one of the data quality criteria that shall be documented. Valid cut-off criteria are based on the quantitative degree of completeness of the overall environmental impacts of the product system (e.g. “covering 85% of the overall environmental impacts”).

- Modelling and handling of multifunctional processes and products

If a process has more than one product as output (co-production e.g. of different chemicals in a synthesis process with valuable by-products), or is treating more than one waste on the input side (co-services), it is called a **multifunctional process**. In consequence, it has more than one function and all of them shall be well defined and specified.

There are three different way to solve multifunctionality. The choice of the most appropriate approach depends among others on the goal situation of the study, available data and information, and the characteristics of the multifunctional process or product.

The first approach is **Subdivision of multifunctional processes:** it refers to the collection of data individually for those of the mono-functional processes that relate to the analysed system and that are contained in the multifunctional process.

The second method is **System expansion:** In practice two different situations can be encountered. The first one is to solve the multifunctionality by expanding the system boundaries and substituting (subtracting) the not required function with an alternative way of providing it, i.e. the process that the not required function supersedes ("substitution"). *Substitution* means to subtract the inventory of another system from the analysed system. This often leads to negative inventory flows. It can even result in negative overall environmental impacts for the analysed system. This means that there is a net benefit of producing the analysed system as the overall impact is more than compensated by the avoided impact the co-functions have elsewhere.

The other situation is when several multifunctional systems are to be made comparable in a comparison study. This would be done by expanding the system boundaries and adding for the given case missing functions and the inventories of the respective mono-functional products.

The third approach is **Allocation**, also called "partitioning", that solves the multifunctionality by splitting up the amounts of the individual inputs and outputs between the co-functions according to some criterion, being a property of the co-functions (e.g. element content, energy content, mass, market price etc.) Allocation should be performed in accordance with the physical (and implicitly also covered: chemical and biological) relationship between the different products or functions. When it is not possible, ISO 14044:2006 recommends performing the allocation according to another relationship between them, such as economic. Since the choice of the allocation method can have a significant impact on the LCA results, the ISO suggests that allocation should be avoided whenever possible. If it can not be avoided, the allocation method should be described and the sensitivity of the results on different allocation methods should be described.

- Impact categories and methods

Impact categories combine material and energy flows, leading to the same kind of impact, in a single indicator. The selection of impact categories must be consistent with the goal of the study and the intended applications of the results, and it must be comprehensive in the sense that it covers all the main environmental issues related to the system.

There are different methods that can be used to perform a Life Cycle Impact Assessment. These methods are continuously researched and developed by different scientific groups based on different methodologies.

The selection or development of any LCIA methods shall meet the following requirements:

- The impact categories, category indicators and characterisation models should enjoy international acceptance;
- The category indicators shall include those that are relevant for the specific LCI/LCA study performed;
- The characterisation model for each category indicator shall be scientifically and technically valid;
- The entirety of characterisation factors should have no relevant gaps in coverage of the impact category they relate to;
- Double counting should be avoided across included characterisation factors, as far as possible, and unless otherwise required by the goal of the study (e.g. as covering impacts of the same elementary flows to more than one impact categories with alternative impact pathways of the elementary flow);
- Value-choices and assumptions made during the selection of impact categories and LCIA methods should be minimised and shall be documented as part of the LCIA method data set documentation and preferably of a more extensive report.

- Types, quality and sources of required data and information

Primary data sources are the producers of goods and operators of processes and services, as well as their associations. Secondary data sources which either give access to primary data (possibly after re-modelling / changing the data) and to generic data are e.g. national databases, consultants, and research groups.

It is recommended to prepare an overview of the principle types of data and information that will be required depending on the type of deliverable of the LCI/LCA study, considering also the general wishes on data and data set quality. Regarding newly collected LCI data this means the needs for representativeness, completeness, and precision.

It is suggested to already identify potential sources for the required data, data sets and information, as far as possible. Well-documented data and data sets should be preferred to allow judging the data appropriateness for use in context of the analysed system and to enable the (potential) critical reviewer to be able to perform an independent verification. The use of externally and independently pre-verified data and data sets are also more convenient, as this provides an assurance of the claimed quality and reduces the effort and costs for review of the LCI/LCA work.

- Special requirements for comparisons between systems

ISO 14040 and 14044:2006 pose a number of further requirements on such studies that make assertions on superiority, inferiority and equality of the compared systems. This is reflecting the consequences that the comparative use of LCA results may have for other companies, institutions and stakeholders that are not directly involved in the study.

All the comparative studies shall guarantee for example these issues:

- The compared system models shall be constructed in an analogous way applying the same rules for system boundaries, LCI modelling principles and method approaches. Secondly, methodological and data assumptions shall be made in an analogous way. In addition, the achieved completeness, accuracy and precision of the data shall be sufficiently similar for the compared systems.
- Calculations on the stochastic uncertainty and accuracy shall support this analysis;
- If included processes / systems of the compared systems are identical for all alternatives, they may be left out of all models.
- Comparison studies based on selected indicators or impact categories shall highlight that the comparison is not suitable to identify environmental preferable alternatives, as it only covers the considered impact.

- The types of the deliverables of the LCI/LCA study

Reporting is a vital element of any LCA. Without clear and effective documentation to experts and communication to decision makers, LCAs can be subject to erroneous and misleading use and will not contribute to improving environmental performance. Reporting shall be objective and transparent, and there should be a clear indication of what has and what has not been included in the study and which conclusions and recommendations the outcome a comparative study supports and what now.

The most commonly used possible types of deliverables are: Life Cycle Inventory study and/or data set; Non-comparative Life Cycle Assessment study i.e. including impact assessment and interpretation; Comparative Life Cycle Assessment study.

Reflecting on the main type of deliverable (i.e. study or data set) and in line with the decision on the target audience(s) and intended application(s), it is important to decide on form and level of reporting, among data set only, non-technical executive summary or detailed report.

2.2 LIFE CYCLE INVENTORY (LCI)

The second step in LCA is called Life Cycle Inventory (LCI) and involves a systematic inventory of all energy and material flows, and emissions connected to the system under investigation during its entire life cycle. All data related to this constructed model are measured, calculated or estimated in regard of the data quality requirements defined in the goal and scope definition phase. As far as possible, data of single steps from the overall investigated process are collected in unit processes, which are small logical parts of the whole process. The result of this inventory is a list of emissions, consumed resources, and non-material impacts. All basic data for further calculations are collected at this step. These data are directly related to the object under investigation; any further finding is the result of natural and social sciences based calculations and therefore only indirectly related to the object under investigation.

A decision between attributional and consequential modelling is to be taken.

The **attributional** life cycle inventory modelling principle is also referred to as "accounting”, “book-keeping”, “retrospective”, or “descriptive”. It depicts the potential environmental impacts that can be attributed to a system (e.g. a product) over its life cycle, i.e. upstream along the supply-chain and downstream following the system's use and end-of-life value chain. Attributional modelling makes use of historical, fact-based, measureable data of known (or at least knowable) uncertainty, and includes all the processes that are identified to relevantly contribute to the system being studied. In attributional modelling the system is hence modelled as it is or was (or is forecasted to be).

The **consequential** life cycle model is also called “marginal” and it aims at identifying the consequences that a decision in the foreground system has for other processes and systems, potentially including political interactions and consumer behaviour changes. To better reflect market and supplier decisions, the market-mechanism models can be restricted by explicitly considering existing and planned future impact in the market and existing or expected policy measures such as e.g. green taxes / incentives and material bans

A key step in consequential modelling is the identification of the marginal processes, i.e. the generic supply-chain, starting from the decision and building the process chain life cycle model around it. [31].

To sum up, these are the steps composing this phase:

- Identifying the processes that are required for the system, making a diagram in which the main processing steps are represented as a flow chart
- Planning the collection of the raw data and information, and of data sets from secondary sources

- Collecting the inventory data for all the system processes and flows, and defying how to deal with missing inventory data. Two approaches can be taken: developing generic LCI data, or obtaining complementary background data as unit processes or LCI datasets from different providers
- Modelling the system by connecting and scaling the data sets correctly to the reference flows in order to provide a functional unit.
- Calculating LCI results, e.g. summing up all inputs and outputs of all the processes within the system boundaries

2.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Life Cycle Impact Assessment consists of the aggregation of the inventory data in support of interpretation. It is carried out because inventory tables are often lengthy and difficult to interpret. There are basic rules for interpreting the inventory result: they must meet the goal and scope definition, data quality assessment, and also an assessment of uncertainty of results has to be provided.

Two steps are compulsory: classification and characterisation, that are firstly done in order to assign each input and output to a specific impact category and to calculate the influence of different kinds of impacts to the same impact category [37].

Classification is done since the results of the Life Cycle Inventory phase include many different emissions. After the relevant impact categories are selected, the LCI results are assigned to one or more impact categories. If substances contribute to more than one impact category, they must be classified as contributors to all relevant categories. For example, CO_2 and CH_4 are both assigned to the impact category "Global Warming Potential". NO_x emissions can be classified to contribute to both Eutrophication and Acidification and so the total flow will be fully assigned to both of these two categories. On the other hand, SO_2 is apportioned between the impact categories of Human Health and Acidification. Human Health and Acidification are parallel mechanisms and so the flow is allocated between the two impact categories.

Characterisation describes and quantifies the environmental impact of the analysed product system. After assigning the LCI results to the impact categories, characterisation factors have to be applied to the relevant quantities. The characterisation factors are included in the selected impact category methods like CML or ReCiPe [37]. Results of the LCI are converted into reference units using characterisation factors. For example, the reference substance for the impact category "Global Warming Potential" is CO_2 and the reference unit is defined as "kg CO_2-equivalent". All emissions that contribute to global warming are converted to kg CO_2-equivalents according to the relevant characterisation factor. Each emission has its own characterisation factor.

Optionally, normalisation and weighting may be applied to further support this.

Normalisation involves displaying the magnitude of impact indicator results relative to a reference amount. For example this can be done for comparison with a reference system. The impact potentials quantify the potential for specific ecological impacts. In the normalisation step the impact category results are compared to references in order to evaluate the scale of the impact. For the normalisation, reference quantities for a reference region or country (e.g. Germany) during a time period (e.g. 1 year) are used. This could be, for example, the overall emission of CO_2-equivalents in Germany within one year, or, the CO_2-equivalents of one person in Western Europe per year. When the results of all impact categories are compared to their references, they can be compared to each other more easily, since it is possible to say which impact indicator result contributes more or less to the overall entity of this impact category.

Weighting uses numerical factors to convert and aggregate indicator results across impact categories, in order to reflect the relative importance of the impacts considered in the study. Weighting may be needed when trade-off situations occur in LCA used for comparisons.

The impact categories and areas of protection shall be checked per default for relevance for the study. Related Life Cycle Impact Assessment **methods** have to be identified too. In life cycle impact assessment methods, two main approaches are used to classify and characterise environmental impacts: the problem-oriented approach (midpoint) and the damage-oriented approach (endpoint). In the problem-oriented approach flows are classified as belonging to environmental impact categories to which they contribute. The damage-oriented methods also start with classifying a system's flows into various impact categories, but the impact categories are also grouped to belong to end-point categories as damage to human health, damage to ecosystem quality or damage to resources. The used end points are easier to interpret and to communicate.
ILCD recently proposed a guidance document with recommendations on the methods to apply for modelling of the most common impact categories [32]. In Table 1, recommended midpoint methods for each selected impact category are reported.

Impact category	Recommended default LCIA method	Indicator
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential
Human toxicity, cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTUh)
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTUh)
Particulate matter/Respiratory inorganics	RiskPoll model (Rabl and Spadaro, 2004) and Greco et al 2007	Intake fraction for fine particles (kg PM2.5-eq/kg)
Ionising radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	Human exposure efficiency relative to U_{235}
Ionising radiation, ecosystems	No methods recommended	
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe	Tropospheric ozone concentration increase
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)
Eutrophication, aquatic	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)
Ecotoxicity (freshwater)	USEtox model, (Rosenbaum et al, 2008)	Comparative Toxic Unit for ecosystems (CTUe)
Ecotoxicity (terrestrial and marine)	No methods recommended	
Land use	Model based on Soil Organic Matter (SOM) (Milà i Canals et al, 2007b)	Soil Organic Matter
Resource depletion, water	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al, 2008)	Water use related to local scarcity of water
Resource depletion, mineral, fossil and renewable	CML 2002 (Guinée et al., 2002)	Scarcity

Table 1 – Impact categories and recommended default LCIA method [32]

2.4 LIFE CYCLE INTERPRETATION

It is useful to structure the results from the LCI and LCIA, and identify the “significant issues” or data elements that contribute most significantly to the results of both the LCI and LCIA for each product, process or service. The identification of significant issues guides the evaluation step. The following three methods should be used for the evaluation [37]:

- **Completeness check**: In the completeness check, any missing or incomplete information will be analysed to see if the information is necessary to satisfy the goal and scope of the study. Missing data have to be added or recalculated to fill the gap or alternatively the goal and scope definition can be adjusted. If the decision is made that the information is not necessary, the reasons for this should be recorded.
- **Sensitivity check**: The sensitivity check determines how the results are affected by uncertainties in the data, assumptions, allocation methods, calculation procedures, etc. This element is especially important when different alternatives are compared so that significant differences or the lack of them can be understood.
- **Consistency check**: The consistency of the used methods and the goal and scope of the study is checked. Some relevant issues to check could be: data quality, system boundaries, data symmetry of time period and region, allocation rules and impact assessment.
- **Contribution analysis**: The contributors to the LCIA results, i.e. the most relevant life cycle stages, processes and elementary flows, and the most relevant impact categories, are identified i.e. by quantifying how high their influence is. Results should be visualised e.g. in stacked columns or the well-known pie charts. The so-called gravity analysis is important for the overall interpretation of the LCI/LCA study and for eventual recommendations.

The Interpretation phase of an LCA has two main purposes:

- During the iterative steps of the LCA and for all kinds of deliverables, the interpretation phase serves to steer the work towards improving the Life Cycle Inventory model to meet the needs derived from the study goal.
- If the iterative steps of the LCA have resulted in the final LCI model and results, and especially for comparative LCA studies (while partly also applicable to other types of studies), the interpretation phase serves to derive robust conclusions and recommendations.

2.5 GABI SOFTWARE® FOR LCA

The LCA is commonly performed with the help of software that supports every stage from data collection and organisation to presentation of results and stakeholder engagement.

The software GaBi 4 (by PE International) used in this study, for example, allows to model processes and to track automatically all material, energy, and emissions flows [37]. Finally, it implements different characterisation methods that enable to calculate impact assessment results.

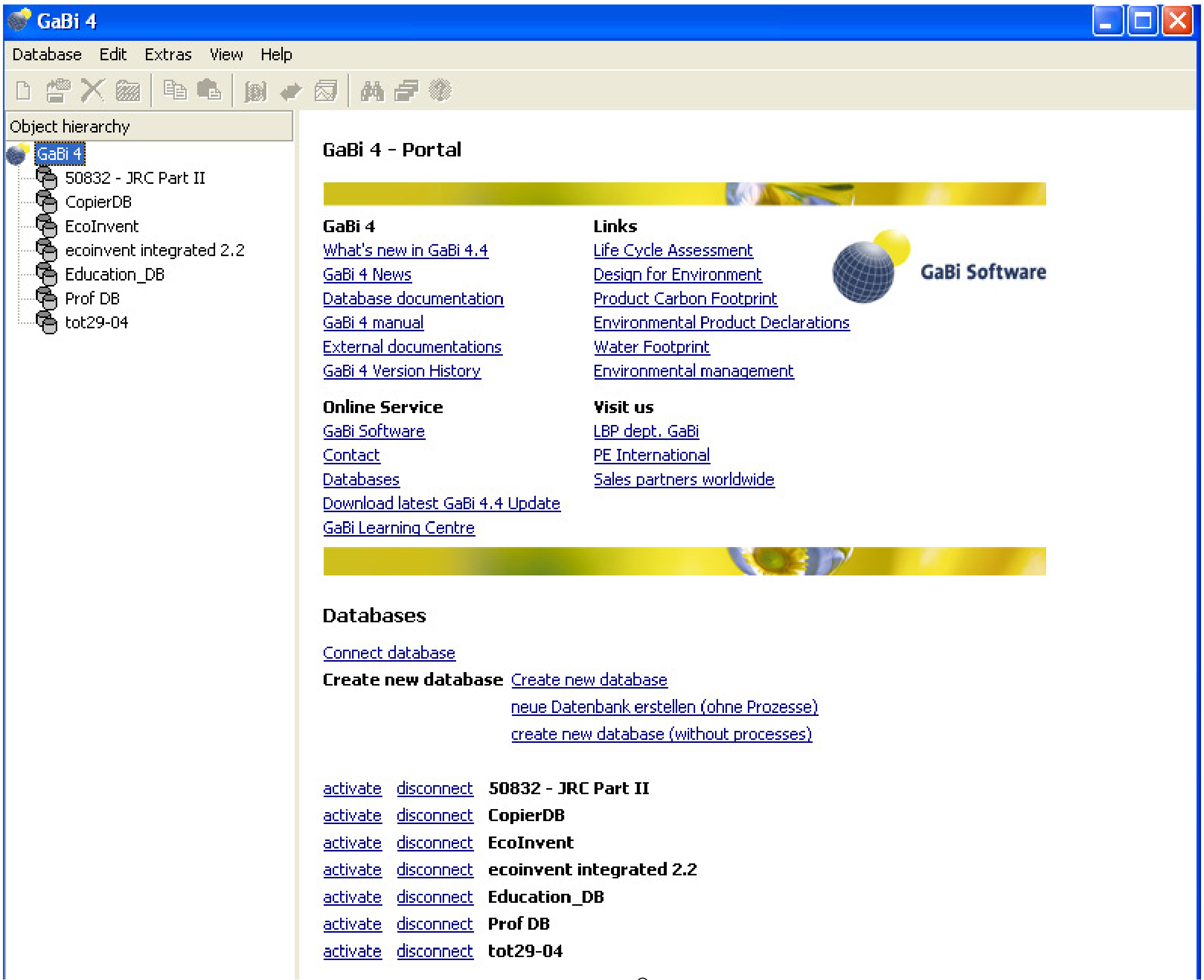

Figure 4 – GaBi Software® (PE International)

3

BIOGAS PRODUCTION AND UTILISATION

"Currently about 80 % of the world's overall energy supply (ca. 400 EJ per year) is derived from fossil fuels. Biomass is by far the most important renewable energy source used to date, supplying 10-15 % of energy supply. On average, in industrialised countries biomass contributes 9-13% of the total energy supply. (…)
Currently biogas plays a smaller, but steadily growing role. Energy recovery from biogas by anaerobic digestion (AD) has been a welcome by-product of sewage sludge treatment for a number of decades. However, biogas has become a well established energy resource, especially through the use of biomass residues or crops. (…)
No single technology or renewable energy source could provide all of the world's future energy supply. Anaerobic digestion is under-utilised today in comparison to technologies for producing liquid biofuels, such as ethanol or biodiesel. At issue is the change in energy vector from liquid to gas. Anaerobic digestion is a versatile technology that requires relatively low levels of parasitic energy demand and can use a wide range of crops including lignocellulosic material such as grass. The energy balance of biogas crop systems is shown to be superior to first generation biofuel technologies, for example for ethanol production.
Anaerobic digestion is a technology which can contribute substantially to the production of renewable electricity, renewable heat and renewable transport fuel. Anaerobic digestion allows for sustainable energy supply, rural employment, and security of energy supply."

IEA Task 37 [15]

Anaerobic digestion (AD) is a biochemical process during which complex organic matter is decomposed in absence of oxygen, by various types of anaerobic microorganisms. The process of AD is common to many natural environments such as the marine water sediments or the stomach of ruminants. In a biogas installation, the result of the AD process is the generation of a *biogas* and a residue, called *digestate.* If the substrate for AD is a homogenous mixture of two or more feedstock types the process is called *co–digestion* [3].

In the first section of this Chapter, the process of anaerobic digestion is introduced (3.3), with typical feedstocks (3.1), pre-treatments (3.2) and residues (3.4).

In Paragraph 3.5, the composition of biogas and the technologies that allow using it are explained.

Finally, the European situation concerning biogas production and utilisation is analysed in Paragraph 3.6.

3.1 FEEDSTOCKS

Biomass is used as substrate for biogas production since it contains carbohydrates (such as cellulose and hemicelluloses), proteins and fats. Only biomass with a large amount of lignin is not suitable because its anaerobic decomposition occurs slowly.

According to the Renewable Energy Directive (2009/28/EC) [34], **biomass** describes the biodegradable fraction of products, wastes and residues of biological origin from agriculture (including vegetable and animal substances), forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction from industrial and municipal wastes.

The most common biomass categories used in European biogas production are listed below.

- Energy crops (e.g. maize, wheat, ley crops)
- Manure (e.g. of cattle, pig)
- Crop residues (e.g. tops and leaves of sugar beet, straw)
- Organic fraction of municipal solid waste
- Food industry waste
- Sewage sludge

The substrates for AD can be classified according to various criteria: origin, dry matter (DM) content, methane yield etc. Table 2 gives an overview on the characteristics of some digestible feedstock types. Substrates with DM content lower than 20% are used for what is called *wet digestion*. When the DM content is as high as 35%, it is called *dry digestion*, and it is typical for energy crops and silages. The choice of types and amounts of feedstock for the AD substrate mixture depends on their DM content as well as the content of sugars, lipids and proteins.

The potential methane yield is one of the important criteria of evaluation of different AD substrates. It is noticeable, that animal manure has a rather low methane yield. This is why, in praxis, animal manure is not often digested alone, but in the most common configuration it is mixed with other *co-substrates* with high methane yield, in order to boost the biogas production. Common co-substrates added for co-digestion with manure and slurries are oily residues from food, fishing and feed industries, alcohol wastes, from brewery and sugar industries, or more often specially cultivated energy crops.

Another reason to choose a substrate is the availability of the material that should guarantee continuous production all over the year, in particular in large scale plants.

Type of feedstock	Organic content	C:N ratio	DM %	VS % of DM	Biogas yield m^3*kg^{-1} VS	Unwanted physical impurities	Other unwanted matters
Pig slurry	Carbohydrates, proteins, lipids	3-10	3-8	70-80	0,25-0,50	Wood shavings, bristles, water, sand, cords, straw	Antibiotics, disinfectants
Cattle slurry	Carbohydrates, proteins, lipids	6-20	5-12	80	0,20-0,30	Bristles, soil, water, straw, wood	Antibiotics, disinfectants, NH_4^+
Poultry slurry	Carbohydrates, proteins, lipids	3-10	10-30	80	0,35-0,60	grit, sand, feathers	Antibiotics, Disinfectants, NH_4^+,
Stomach/intestine content	Carbohydrates, proteins, lipids	3-5	15	80	0,40-0,68	Animal tissues	Antibiotics, disinfectants
Whey	75-80% lactose 20-25% protein	-	8-12	90	0,35-0,80	Transportation impurities	
Concentrated whey	75-80% lactose 20-25% protein	-	20-25	90	0,80-0,95	Transportation impurities	
Flotation sludge	65-70% proteins 30-35%lipids	-				Animal tissues	Heavy metals, disinfectants, organic pollutants
Ferment. slops	Carbohydrates	4-10	1-5	80-95	0,35-0,78	Non-degradable fruit remains	
Straw	Carbohydrates, lipids	80-100	70-90	80-90	0,15-0,35	Sand, grit	
Garden wastes		100-150	60-70	90	0,20-0,50	Soil, cellulosic components	Pesticides
Grass		12-25	20-25	90	0,55	Grit	Pesticides
Grass silage		10-25	15-25	90	0,56	Grit	
Fruit wastes		35	15-20	75	0,25-0,50		
Fish oil	30-50% lipids	-					
Soya oil/margarine	90% vegetable oil	-					
Alcohol	40% alcohol	-					
Food remains			10	80	0,50-0,60	Bones, plastic	Disinfectants
Organic household waste						Plastic, metal, stones, wood, glass	Heavy metals, organic pollutants
Sewage sludge							Heavy metals, organic pollutants

Table 2 - The characteristics of some digestible feedstock types [3]

3.1.1 Energy crops

The concept of crops for methane production was early investigated in the 1930's in the USA (Buswell and Hatfield, 1936), in the 1950's in Germany (Reinhold and Noack, 1956), and in the 1980's in New Zealand (Stewart et al., 1984). Although the digestion of crop material was demonstrated, the process was hardly applied in practice because it was not considered to be economically feasible. Crops, crop by-products and waste materials were occasionally added to stabilise anaerobic waste digesters.

In the 1990's steadily increasing oil prices and improved legal framework conditions, stimulated energy crop research and development. In some countries it can be directly attributed to the favourable supportive national legal framework coupled with the tariffs paid for renewable electricity.

Many varieties of crops are now cultivated with no food purposes but specifically to produce solid, liquid or gaseous fuels. These are called *energy crops*.

Commonly, energy crops are digested together with manure (co-digestion) in order to have total solids (TS) content suitable to be fed to the digester. The use of solely energy crops requires the addition of nutrients and water or the recirculation of the liquid fraction of digestate in order to maintain homogeneous conditions.
Most crops have been found to have similar methane yields [m^3/tVS] but different crops give different biomass yields [t/ha] (see Table 3). Consequently, from an agricultural point of view a better measure to compare overall yield is the energy yield per hectare of cultivated land.
According to the balance between their biomass yield, the methane yield and the availability of the proper condition for their growth, the most common energy crops used in biogas production are **maize** and various **grass** crops. Root crops like beets and potatoes can also achieve high yields per hectare, but are comparably seldom used for anaerobic digestion, mainly due to operational drawbacks associated with soil contamination and hence sand accumulation inside the digesters. Other grains are needed for crop rotation (e.g. rye), but they give lower biomass yield per hectare, compared for example to maize or beets.
As a consequence crops should be carefully selected, depending on local climate conditions, availability of irrigation water, resistance to diseases, and last but not least, biomass yield per hectare [15].

Crop	Crop yield[1)] t DS. ha^{-1}	Measured methane yield[2)] $m^3 . t^{-1}$ VS	Calculated methane yield[3)] $m^3 . ha^{-1}$
Maize (whole crop)	9-30	205-450	1,660 - 12,150
Wheat (grain)	3.6-11.75	384-426	1,244 - 4,505
Oats (grain)	4.1-12.4	250-365	922 - 4,073
Rye (grain)	2.1	283-492	535 – 930
Barley	3.6-4.1	353-658	1,144 - 2,428
Triticale	3.3-11.9	337-555	1,000 - 5,944
Sorghum	8-25	295-372	2,124 - 8,370
Grass	10-15	298-467	2,682 - 6,305
Red clover	5-19	300-350	1,350 - 5,985
Alfalfa	7.5-16.5	340-500	2,295 - 7,425
Sudan grass	10-20	213-303	1,917 - 5,454
Reed Canary Grass	5-11	340-430	1,530 - 4,257

Table 3 – Range of estimated crop, methane and energy yields per hectare [15]

3.1.1.1 Maize

Maize is a member of the family Gramineae and comes originally from Mexico. The plant grows as tall as 2,5 m and has a pith-filled stalk up to 5 cm in diameter. It is relatively drought-tolerant and will also grow on poorer soils. As a tropical-subtropical plant, maize is not frost resistant. The optimum temperature for growth is 30 °C [39]. It is therefore usually grown in a warmer climate but new species have been developed that are able to stand the colder climate of Northern Europe [71].

Whereas maize is primarily grown as livestock feed (*silage maize*) in Europe and in North America, in many developing and newly industrialising countries it is one of the most important staple foods (grain maize). In 2006, Germany produced nearly 3,4 million t of grain maize, representing 0.5 % of worldwide production, but nearly 47 million t of silage maize [39].

In 2007, the area planted with genetically modified maize cultivars amounted to 35,2 million hectares, which represents 24% of the worldwide maize production area [39].

Modern maize monocultures have a number of adverse effects on the environment. Groundwater is contaminated by nitrate leaching associated with the use of nitrogen fertilisers and by herbicides. The soil is endangered by prolonged fallow periods, and is compacted and eroded by heavy farm machinery. In addition, conventional maize cultivation practices require a high energy input. Maize monocultures are low biological diversity agro-ecosystems. Various measures can be employed to mitigate ecological impacts: increasing the number of different crops within the crop rotation, reducing energy inputs with a well-balanced fertilisation programme, protecting the soil from erosion and compacting thanks to mulch seeding, better ground cover and reduced tillage [39].

As seen in Table 3, maize can reach the highest methane yield per hectare of cultivation. However, using maize as the only substrate may cause problems since it can not guarantee a large spectrum of nutrients needed by anaerobic bacteria [16]. Anyway, nowadays maize is the most widely used co-substrate [15].

Finally, maize cultivation as feedstock in anaerobic digestion could result in severe competition between energy (maize is also used as substrate for ethanol production because of the high sugar content in its grains) and food supplies (effects for indirect land use change because of the displacement of food production provided by the land before the change), which is probably not favourable in the long term [16].

3.1.1.2 Grass

Grasslands play an important role in global agriculture, covering about 3,4 10^9 ha, i.e. 69% of the world's agricultural area or 26% of total land area. Grassland use is characterised by various modes and intensities. Currently, grasslands are predominantly used in animal husbandry as a principal source of food for ruminants [62]. At present, the first harvest of grasses is utilised as forage, as it is the most suitable for animal feed. Usually only the first harvest is fertilised while it is not common to fertilise, or even harvest, the second or third growth [66].

Grassland cultivation is also a good environmental use of arable land. Grasses take up nutrients efficiently and arable land is covered in autumn and winter by grasses, which decrease nutrient leaching. Grass has ecological functions that include carbon storage, protection of soil from erosion, ground water formation, and habitat function [66].

Permanent grassland is defined as land used for five years or more for herbaceous forage crops, either cultivated or growing wild.

Looking at the global trends in grassland area, ruminant numbers and milk and meat production, it can be seen that in developed countries ruminant numbers have been declining constantly during the last three decades while the production of milk and meat increased. Improved animal performance, changed diet composition with higher percentages of concentrates, and grassland intensification have led to the situation that less and less grassland is needed for farming purposes. In the same period the national demands for ruminant products have been falling. Animal production is expected to continue to decrease in importance. An increasing amount of surplus grassland already exists in many developed countries. For the EU-27 the surplus grassland in 2020 is estimated at 9,2-14,9 10^6 ha, i.e. 13-22% of the permanent grassland [62]. There is still a considerable risk of its conversion into surplus land if the land is not used productively. Nevertheless usage of grassland as a renewable source of energy through biogas production will contribute significantly to the protection of the environment [53].

Bioenergy displaces animal husbandry as the original type of grassland use. Grasslands could contribute a share of 16-19% of the energy crops potential and 6-7% of the total bioenergy potential without occupying area that is used for animal feeding. Grassland biomass is suitable in many ways for producing energy: it is used as a feedstock for biogas production and as solid biofuel for combustion. In Germany and Austria grass silage is used as a feedstock in 50% and more of the biogas plants and is the second most frequent crop feedstock after maize silage [62]. Grasses have the advantage of being familiar to farmers and suitable for harvesting and storing with existing methods and machinery. The grasses can also be included in current crop rotation practices. Because grasses have been bred for animal feed, they are often characterised by good digestibility [66].

The best agricultural practice that can realistically be implemented to approach a sustainable animal production system and landscape conservation in the area considered, bearing in mind the ongoing reduction of the number of animals, is to keep the first two harvests with the higher feeding values for animal feeding. The last two harvests are tedded, silaged and fed to an anaerobic digester [38].

Due to the lower energy content and digestibility of this grass, the methane productivity of the grass silage is lower than maize silage potential [38]. Non-cultivated plant species may vary in terms of their chemical constituents. Hence, methane yields from grassland, which often does not consist of pure stands of single grass species but of plant communities, could possibly depend on the mixture of species within the vegetation [62].

Concerning the introduction of cultivated temporary grass in the usual crop rotation, it requires additional soil preparation, sowing and weeds control [38].

3.1.2 Manure

In EU-27, more than 1500 million tons of manure from animal production, mainly from cows and pig farms, are produced every year. Manure is primarily composed of organic material and water. Manure production varies by animal type and is proportional to the animal's weight. A typical 1400-pound[1] dairy cow produces about 112 pounds of manure per day [20].
When untreated or managed poorly, manure becomes a major source of ground and fresh water pollution, pathogen emission, nutrient leaching, and ammonia and greenhouse gas release. The livestock sector is responsible for 18% of the greenhouse gas emissions and for 37% of the anthropogenic methane. Besides, it is responsible for 65% of anthropogenic nitrous oxide and 64% of anthropogenic ammonia emissions [42].
If handled properly, it turns out to be renewable energy feedstock and an efficient source of nutrients for crop cultivation. For example, the animal farms must store the produced slurry in specially designed tanks for up to 6-9 months before its application as crop fertiliser. The application period lasts 4-6 months, close to or during the growing seasons, depending on the country, in order to reduce nutrient leaching to ground water.
Biogas production from anaerobic digestion of animal manure is an effective way of reducing greenhouse gas (CH_4 and N_2O) and ammonia emissions from manure storage facilities. The digestion of manure alone does not result in high biogas yield, but its high buffer capacity and content of diverse nutrients has a positive impact on the process stability. Therefore, high methane yield can be achieved through co-digestion of manure with energy crops. The digestate after the process can be further refined and used as organic fertiliser, rich in nitrogen, phosphorous, and potassium as well as in other macro- and micro-nutrients necessary for plants growth. Usage of large amount of animal manure for bioenergy purpose will reduce the nutrients runoff and diminish the contamination of surface- and ground- water resources by closing and optimizing the recirculation loop of biogas production [42].

[1] 1 pound = 453,6 g; 1400 pounds = 635 kg; 112 pound = 50,8 kg

3.2 PRE-TREATMENTS

3.2.1 Energy crops and crops residues

In order to increase the degradation rate of energy crops and residues, pre-treatments by mechanical, thermal, chemical, or enzymatic processes can be applied.
The decomposition process is faster with **decreasing particle size** but it does not necessarily increase the methane yield. Feedstock crushing is usually needed to optimise the feeding system by application of an extruder or by ultrasonic treatment of a side stream of the fermenter [73].

Energy crops are suitable for ensilage because they have a total solid (TS) content between 30-40% [15]. **Ensilage** is a common step for the conservation and storage of the substrate. For optimal ensiling conditions, the energy crops should be cut to particle length of 10–20 mm. It is necessary to compact the harvested crops in a confined environment (silo) or to cover it by a plastic wrap. The natural biochemical process that occurs in the silo in absence of oxygen converts the soluble carbohydrates contained in the plant matter to lactic acid, acetate, propionate, and butyrate which inhibit the growth of detrimental microorganisms by a strong drop in pH to values between 3 and 4. This stabilizes the plant material during storage and allows the continuous using in biomethanation over the year [73].

Depending on the total solids content that is allowed in the digester, solid substrates can be **diluted** with water or with the liquid fraction of digestate in order to achieve pumpable slurries [73].

Finally, thermal pressure hydrolysis and addition of hydrolytic enzymes have shown to increase biogas yield, but they are not so commonly applied because they are not economically convenient.
Treatment by **thermal pressure hydrolysis** (230 °C, 20–30 bars) results in the splitting of organic polymers by hydrolysis into short chains that are biologically easily available compounds. The addition of **hydrolytic enzymes** can improve the decomposition of structural polysaccharides; it reduces the viscosity of the substrate mixture in the digester significantly and avoids the formation of floating layers [73].

3.2.2 Manure

According to the European Union Animal By-Products Regulation (1774/2002 EC), a phase of **pasteurization** at 70 °C for 1 hour is required before or after anaerobic digestion to reduce pathogenic bacteria in animal by-product. **Sterilization**, at 133 °C and 3 bar of pressure for 20 minutes, is more efficient in avoiding bacterial spores and recontamination. These processes require thermal energy.

However, anaerobic digestion is able to reduce pathogens from all kind of animal sludge. Under high temperature (thermophilic) and long retention time, it obtains acceptable sanitation effects and therefore it is considered sufficient for some categories of animal by-product.

Only few studies have tested the reduction of pathogens affecting plants and the inactivation of seeds [50].

It is possible to **separate liquid and solid fraction** of the raw slurry before the digestion: the digestion of the solid fraction and the spreading of the liquid undigested one is suitable for dilute manure with low biogas yield. The separation can be done with a decanter or with a screw press.

3.3 THE BIOCHEMICAL PROCESS OF ANAEROBIC DIGESTION

The process of biogas formation is a result of linked process steps, in which the initial material is continuously broken down into smaller units. Specific groups of micro-organisms are involved in each individual step. These organisms successively decompose the products of the previous steps. The simplified diagram of the AD process, shown in Figure 5, highlights the four main process steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

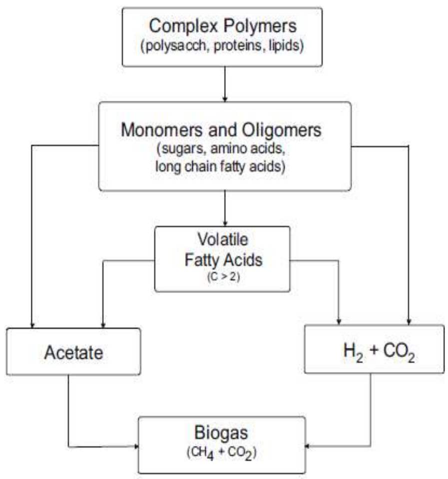

Figure 5 – The chemical process of anaerobic digestion [73]

Hydrolysis is theoretically the first step of AD. Complex polymers such as proteins, polysaccharides and lipids are hydrolyzed into their monomers by the enzymes that some facultative anaerobic bacteria (such as *Clostridium, Bacillus, and Staphilococcus*) produce.
Then, these microorganisms convert the product of the hydrolytic phase into, mainly, acetate, carbon dioxide and hydrogen (70%) as well as into volatile fatty acids (VFA) and alcohols (30%). This phase is called **acidogenesis**.
In the third step (**acetogenesis**) products from acidogenesis which can not be directly converted to methane by methanogenic bacteria are converted into methanogenic substrates by some bacteria as *Acetobacterium woodii* or *Clostridium aceticum*. Volatile fatty acids with carbon chains longer than two units and alcohols with carbon chains longer than one unit are oxidized into acetate and hydrogen.
Finally, during **methanogenesis** two groups of obligate anaerobic methanogenic bacteria produce methane, carbon dioxide and water. The first group uses acetate (*Methanosarcina barkeri, Methanococcus mazei, and Methanotrix soehngenii*) while the second one performs the reaction with H_2 and CO_2, following these pathways:

1) $CH_3COOH \rightarrow CH_4 + CO_2$

2) $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Other components of biogas such as H_2S and NH_3 are by-product of the volatile fatty acids production. Their concentration depends on their amount in the original substrate [73, 61].

3.3.1 AD parameters

It is important to guarantee particular conditions in the reactor in order to obtain high efficiency of biogas production.

A balanced process requires that acid production and methane production runs at the same **speed**. The stability of the AD process is reflected by the concentration of intermediate products like the VFA. If acid concentration rises because the first degradation runs too fast, pH drops and inhibits methanogenic bacteria, which can operate between 6,5<pH<8,2. This occurs in case of biomass rich in carbohydrates that are cracked into monomers in few hours. If the biomass is degraded too slowly, methanation is limited as well [73]. However, the accumulation of VFA will not always be expressed by a drop of pH value, due to the buffer capacity of the digester, through the biomass types contained in it. Animal manure e.g. has a surplus of alkalinity, which means that the VFA accumulation should exceed a certain level, before this can be detected due to significant decrease of pH value [3].

The **pH** value of the AD substrate influences the growth of methanogenic microorganisms and affects the dissociation of some compounds of importance for the AD process (ammonia, sulphide, organic acids). The optimum range is for hydrolysis 5,5-6,5 and for methanation 6,8-7,2 [73].

The value of pH in anaerobic reactors is mainly controlled by the bicarbonate buffer system, as explained before. It is then important to note that the pH-value can be a quick, relatively reliable and cheap way of registering system imbalance in more weakly buffered systems, such as AD of various wastewater types [3].

In addition, microorganisms need **nutrients** to grow and to react. The feedstocks should guarantee a ratio of C:N:P:S = 600:15:5:1 [73]. Other micronutrients are also required: ions as Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, S^{2-}, Cu^{2+}, Ni^{2+}, Cr^{6+}, Zn^{2+}, Pb^{2+}, Mn^{2+}, Fe^{2+} are essential but an excess could cause damages. It is important to analyse their presence in the materials fed into the reactor.

Another factor, influencing the activity of anaerobic microorganisms, is the presence of toxic compounds: for example, possible inhibition has been reported from long chain fatty acids such as oleate and stearate, from some antibiotics, from phenols, chloroform and heavy metals higher in concentration than the essential [14]. They can be brought into the AD system together with the feedstock or are generated during the process. The application of threshold values for toxic compounds is difficult, on one hand because these kind of materials are often bound by chemical processes and on the other hand because of the capacity of anaerobic microorganisms to adapt, within some limits, to environmental conditions, herewith to the presence of toxic compounds.

Furthermore, the **temperature** is an important parameter. Low temperature facilitates volatile acids production and may cause their accumulation, but it is an economic solution. On the contrary, high temperature is less suitable for acids production and requires more energy input. However, it increases the speed of the whole process and avoids the growth of pathogenic bacteria. Therefore, the typical range of temperature is between 35-42 °C for the so-called *mesophilic* condition and 45-60 °C for *thermophilic* conditions [73]. The decision is linked to economical and strategic evaluation.

Finally, the **retention time (HRT)** has to be adequate to assure the growth of methanogenic population. The higher is the temperature, the less retention time is required, as shown [61]:

Temperature [°C]	**HRT [days]**	
	min	**max**
20	11	28
25	8	20
30	6	14
35	4	10
40	4	10

Table 4 – The correlation between temperature and retention time in the digester [61]

3.3.2 Processes and configurations

The core of a biogas plant is the digester, an air proof reactor tank where the decomposition of feedstock takes place, in absence of oxygen, and where biogas is produced. Common characteristics of all digesters are that they have a system of feedstock feed-in as well as systems of biogas and digestate output. In European climates anaerobic digesters have to be insulated and heated.

There are various types of biogas digesters, operating in Europe and around the world. Digesters can be made of concrete, steel, brick or plastic, shaped like silos, troughs, basins or ponds, and they may be placed underground or on the surface. The size of digesters determines the scale of biogas plants and varies from few cubic meters in the case of small farm household installations to several thousands cubic meters, like in the case of large commercial plants, often with several digesters [3].

Type of reactor:

- Continuous Stirred Tank Reactor (CSTR)
- Plug Flow (PF)
- Batch

Number of stages

- One stage
- Two stage

According to different values of the parameters or to special plant configurations, many kinds of processes can be identified.

Temperature

- Mesophilic (35-42 °C) [73]
- Thermophilic (45-60 °C) [73]

Water content

- Wet digestion (<10% TS) [14]
- Dry digestion (20-35% TS) [14]

The running of the reactors requires energy consumption for pumping, stirring and heating.

After storage and pre-treatment, AD feedstock is fed into the digester. The **feeding** technique depends on the feedstock type and its pumpability. Pumpable feedstock is transferred from storage tanks to the digester by pumps. Two types of pumps are frequently used: the centrifugal (rotating) and the displacement pumps (turning piston pumps, eccentric screw pumps). Feedstock types which are non-pumpable can be tipped/ poured by a loader into the feeding system and then fed into the digester (e.g. by a screw pipe system) [3].

A minimum **stirring** of biomass inside the digester takes place by passive stirring. This occurs by insertion of fresh feedstock and the subsequent thermal convection streams as well as by the up-flow of gas bubbles. As passive stirring is not sufficient for optimal operation of the digester, active stirring must be implemented, using mechanical, hydraulic or pneumatic equipment. Up to 90% of biogas plants use mechanical stirring equipment.

The digester content must be stirred several times per day with the aim of mixing the new feedstock with the existing substrate, inside the digester. Stirring prevents formation of swimming layers and of sediments, brings the micro-organisms in contact with the new feedstock particles, facilitates the up-flow of gas bubbles and homogenises distribution of heat and nutrients through the whole mass of substrate.

Stirrers can run continuously or in sequences. Experience shows that stirring sequences can be empirically optimised and adapted to a specific biogas plant (tank size, feedstock quality, tendency to form floating layers etc.). After the supply of the first feedstock load and the start-up of the plant, the optimum duration and frequency of stirring sequences and adjustment of stirrers will be determined by experience, through continuous monitoring of the digester performance [3].

Heat demand depends on the location of the digester, the insulation and seasonal variations. Heating the feedstock can be done either during the feeding process (pre-heating) through heat exchangers or it can be done inside the digester, by heating elements, hot steam etc. Pre-heating the feedstock during feeding has the advantage of avoiding temperature fluctuations inside the digester. Many biogas plants use a combination of both types of feedstock heating [3].

Today, wet digestion processes dominate in the agricultural sector. The most common reactor is a covered vertical CSTR equipped with mechanical submerged motor stirring equipment. If the TS content is high, slow rotating paddle are preferred, with an outsider motor. Also pneumatic and hydraulic stirrers are available. Most of these fermenters are operated at mesophilic temperature [73].

Dry fermentation is suitable for monofermentation of energy crops in batch processes without mechanical mixing. It is necessary however to add water or the inoculum from a previous batch digestion to reach the proper TS content. At least three parallel digesters, operating with different start-up times, are required to achieve a constant biogas production.
Dry fermentation is possible also in continuous horizontal or vertical PF reactors mechanically mixed: this type of digestion is known in the treatment of municipal organic waste [73].

The two-stage system consists of a high-loaded main fermenter (a horizontal PF with a low rotating horizontal paddle mixer) in series with a low-loaded secondary fermenter. The aim is to divide hydrolyses and methanation in order to reach the optimum pH range for each step [60].

3.4 DIGESTATE

Digestate is the solid and liquid residue of anaerobic digestion.
Compared to raw material, anaerobic fermentation provides a significant or total inactivation of seeds, bacteria, viruses, fungi and parasites that may be contained in the feedstock. It also reduces volatile organic compounds responsible for unpleasant odours.

Digestate is spread as fertiliser to recycle nutrients and to avoid consumption of artificial products. In fact, the quantity of nutrients contained in the feedstock is the same as in the digestate. However, the mineralisation of the nutrients makes them more easily available to crops.
As an example, nitrogen is considered. The mainly nitrogen content of a biomass is partly mineral (in form of ammonium), partly organic (in proteins). During anaerobic digestion, a percentage of the organic nitrogen is converted into ammonium, although the total nitrogen remains the same. The utilisation percentage, defined as the relative quantity of mineral fertiliser nitrogen necessary to obtain the same yield of crop as the quantity of total nitrogen supplied in digestate, should be equivalent to the share of ammonium. However, when digestate is applied to a field surface some ammonia volatilisation will take place after application. Unfortunately, this high ammonia content increases the risk of volatilisation during and after application. As a result the utilisation percentage will decrease; it is important to minimise the surface area of digestate that is exposed to air after application so as to avoid ammonia volatilisation. This can be achieved by different methods of spreading (trailing shoes, injection).
However, anaerobic digestion treatment improves the flow properties of raw materials so the digestate can penetrate faster in the soil reducing the risk of ammonia emissions.

The application of digestate or any crop fertiliser at times of the year when there is little plant uptake (e.g. autumn and winter) can result in nutrient leaching and runoff into ground and surface waters (e.g. of nitrates and P).
Digestate must therefore be stored until the correct time for application. When digestate is stored in open tanks, ammonia and methane gases are given off. These emissions can be reduced if the surface of the liquid is covered by a protective layer. This layer can be a natural crust of at least 10–20cm, a floating layer of plastic pieces, clay pebbles or chopped straw, etc.
Two other methods that minimise both methane and ammonia losses are to cover the digestate storage tanks with air tight membranes or to use flexible storage bags.

Another possibility is to separate mechanically the digestate, by creating two outputs, a liquid and a fibrous material. They need then to be stored and handled separately; it is particularly important to underline that the higher dry matter and fibrous fraction should be stored without disturbance or even composted, in order to avoid any methane emission.
Some advantages of digestate separation for farmers are that it will produce a pumpable liquid fraction, minimising also the requirement for mixing prior to spreading and the volume of storage. In addition, the efficiency in nitrogen uptake improves.
Concerning the stackable dry fraction, it creates the potential to export separated fibre and nutrients.

Quality management of digestate involves a range of permits and quality standards to ensure the safety and value of digestate as a fertiliser, soil conditioner or growing medium.
Farmers who use their own on-farm produced feedstock (such as manure or crops) should carry out their own quality controls. These should include periodic sampling and analysis of feedstock to determine its biogas potential (e.g. dry matter, nutrients and volatile solid content and pH levels). The digestate should be analysed similarly before application, to aid accurate fertiliser planning.
When off-farm material (e.g. industrial organic residues, biodegradable fractions of municipal solid waste, sewage sludge etc.) is co-digested, the digestate can contain various amounts of hazardous matter (biological, chemical and physical) that could pose risks for animal and human health or cause environmental pollution. These contaminants can include residues of pesticides and antibiotics, heavy metals and plant and animal pathogens. In each EU country, stringent regulations govern the admissible feedstocks for anaerobic digestion and uses of the digestate as an organic fertiliser [50].

3.5 BIOGAS

Biogas is a mixture of gas mainly composed by methane and carbon dioxide. The composition and properties of biogas vary to some degree depending on feedstock types, digestion systems, temperature, retention time etc.

Table 5 contains some average biogas composition values, found in most of the literature.

Compound	Chemical symbol	Content (Vol.-%)
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapour	H_2O	2 (20°C) -7 (40°C)
Oxygen	O_2	<2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Hydrogen sulphide	H_2S	<1

Table 5 – Average biogas composition [3]

Typical undesired substances in biogas coming from agricultural feedstocks are:

- **Sulphur gases**: oxidized sulphur compounds (sulphate and sulphide) are corrosive in presence of water. The main component is hydrogen sulphide, which is corrosive in presence of water and thus reactive with most metals. Moreover, a toxic concentration of H_2S (>5 ppm) may remain in the biogas [63].
- **Water vapour**: this may condense in gas pipelines and cause corrosion in compressors, gas storage tanks and engines due to reaction with H_2S, NH_3 and CO_2 to form acids.
- **Ammonia**: is corrosive while dissolved in water.
- **Dust and particles**: may clog gas storage tanks and compressors.

In addition, biogas can contain halogenated compounds which are typical of landfill gas because they originate from volatilisation of solid waste components. Siloxanes, volatile silicones bonded by organic radicals, occur in landfill gas or in sewage sludge because they are contained in cosmetics, shampoos and detergents.

3.5.1 Biogas utilisation

Biogas can replace fossil fuels and can be used in different devices and with different purposes:

- **Direct combustion** in boilers or burners for heat production.

- Combined heat and power (**CHP**) generation.

Before the injection into the engine, biogas should be drained and dried to prevent damage to the gas utilisation units. Most gas engines have maximum limits for the content of hydrogen sulphide, halogenated hydrocarbons and siloxanes in biogas.

The most common types of CHP plants are block type thermal power plants (BTTP) with combustion motors that are coupled to a generator. Generators usually have a constant rotation of 1500 rpm (rotations per minute) in order to be compatible with the grid frequency. Motors can be Gas-Otto, Gas-Diesel or Gas-Pilot Injection engines. Both, Gas-diesel and Gas-Otto engines are operating without ignition oil. The difference between these engines is only in the compression phase.

The electricity produced from biogas is generally used as process energy for electrical equipment such as pumps, control systems and stirrers, while the excess is sold. In many countries with high feed-in tariffs for renewable electricity, all the produced electricity is sold to the grid and the process electricity is bought from the same national electricity grid.

An important issue for the energy and economic efficiency of a biogas plant is the utilisation of the produced heat. Many of the early generations of biogas plants have being established exclusively for electricity purposes, without consideration for the utilisation of the produced heat. Nowadays, the heat utilisation is considered a very important aspect for the economy of the plant. Usually, a part of the heat is used for warming the digesters but the remaining amount can be used for external needs, such as for district heating or as process heat in neighbouring plants [3].

- Injection as **CNG** (Compressed Natural Gas) into the natural gas grid or compression and use as vehicle fuel. Prior to that, biogas must undergo a cleaning and upgrading process, where all contaminants, as well as carbon dioxide, are removed and the content of methane is increased from the usual 50-75% to more than 95%. The upgraded biogas is often named **biomethane**.

3.5.2 Cleaning

This step is sometimes required before the upgrading process or the combustion of the gas in engines, in order to prevent corrosion on the mechanical equipment.

3.5.2.1 Removal of water

Pipeline quality standards require a maximum water content of 100 mg/m^3 water.

All the techniques to remove water are applied at elevated pressures in order to achieve lower dew points. The dew point required is at least 10 °C below the 99% winter design temperature for the local geographic area at atmospheric pressure [63].

Water can be removed by:

- **Cooling**: the condensed water drops are entrapped and removed with different techniques, such as demister, cyclone separators, moisture traps or water taps.
- **Compression**: the gas is compressed before cooling and then expanded to the desired pressure.
- **Adsorption with SiO_2**, activated carbon or molecular sieves.
- **Absorption in glycol solutions or hygroscopic salt.**

These techniques can remove also dust and foam.

3.5.2.2 Removal of H_2S

Engines allow for a concentration of hydrogen sulphide between 80 and 300 ppm (on average, 200 ppm) [68]. Therefore the excess, if present, must be removed.

Concerning the injection in the gas grid, some upgrading technology can retain H_2S without preliminary cleaning step, while other methods need this additional phase.

- **Internal biological H_2S reduction**

The biological treatment with autotrophic micro-organisms and introduction of air in the reactor is the most applied primary method at agricultural biogas plants using CHP [9]. Microorganisms of the species Thiobacillus and Sulfolobus make the following reactions, causing the precipitation of sulphur thanks to the injection of 2-12% air in the gas in the digester:

3) $2H_2S + O_2 \rightarrow 2S + 2H_2O$

Addition of oxygen and nitrogen is not allowed if the biogas is upgraded and used as vehicle fuel or biomethane. Indeed, removal of N_2 and O_2 is difficult and costly. In addition, biogas in air is an explosive mixture, so safety measure should be taken to avoid high excess of air concentration.

For all these reasons, this technique is used with CHP unit where a higher H_2S content is permitted.

- **External biological H_2S reduction**

This is a biological treatment with autotrophic micro-organisms and introduction of air (5-10%) in a trickling filter: the oxidation of hydrogen sulphide follows the same principle as seen before but bacteria grow on a packing material of a filter. The gas flow passes through the filter while leaving the digester [11].

This method allows for high control but it has higher specific costs [9].

- **Internal chemical precipitation using iron salts (sulphide precipitation)**

Insoluble iron sulphide FeS is produced because of the introduction of Fe ions inside the digester. Iron sulphide precipitates and it is removed with the digestate. This method allows of concentrations of less than 100 ppm of H_2S [11].

An alternative process consists in dosing iron hydroxides in solid form. This method has lower operational costs and handling hydroxides is easier.

- **Chemical precipitation using iron oxides/hydroxides**

Adsorption on oxide-coated ($Fe(OH)_3$ or Fe_2O_3) support material: according to the following reactions:

4) $Fe_2O_3 + 3H_2S \rightarrow Fe_2S_3 + 3H_2O$

5) $2Fe(OH)_3 + 3H_2S \rightarrow Fe_2S_3 + 6H_2O$

The gas is cleaned while it passes through a reaction bed filled with pressed minerals or wood chips. Two columns are needed; one bed undergoing regeneration while the second one is removing H_2S.

- **Chemical absorption into iron-chelated solution**

This technology allows recovering elementary sulphur, as follows, thanks to the iron-chelated solution that functions as a pseudo-catalyst that can be regenerated. The most common chelate agent is EDTA [21].

6) $H_2S(aq) \leftrightarrow 2H^+ + S^{2-}$

7) $S^{2-} + 2Fe^{3+} \leftrightarrow S + 2Fe^{2+}$

8) $\frac{1}{2}O_2 + 2Fe^{2+} \rightarrow 2Fe^{3+} + 2OH^-$

9) $H_2S + \frac{1}{2}O_2 \rightarrow S + H_2O$

The removal of H_2S from the biogas is almost complete but the system is designed for high load and is rarely used in biogas plants [57]. The sulphur produced can be removed easily by sedimentation or filtration operation and can be sold as a raw material.

- **Chemical absorption: washing with water or water with NaOH or $Fe(OH)_3$**

Since physical absorption of hydrogen sulphide with water is not so common because it is not economically convenient, it is useful to add NaOH that reacts with H_2S. This technique allows reducing the amount of water required and therefore the volume of the reactor [57].

- **Adsorption / catalytic oxidation using impregnated activated carbon**

H_2S is adsorbed on the inner surfaces of engineered activated carbon with defined pore sizes. Addition of oxygen oxidizes H_2S to S that binds to the surface. Since O_2 addition is not allowed if the gas is injected with the natural gas, the activated carbon is mostly doped with potassium iodide (KI) or impregnated with permanganate or potassium carbonate (K_2CO_3) as catalysers. H_2S removal is extremely efficient [57].

3.5.3 Upgrading

The aim of upgrading processes is to adjust the lower calorific value (LHV), the Wobbe index and other parameters in order to achieve the pipeline or the road engines specifications. It consists mainly in the separation of the methane and the carbon dioxide: the methane-rich stream is then compressed and injected into the gas grid, or used as transport fuel, while the off gas containing mainly CO_2 is, in most cases, released in the atmosphere, but could be stored, if carbon capture and storage technologies would be available in the future.

The **higher heating value** (HHV) of biogas is determined mainly by the methane content in the gas and it corresponds to the energy that is released when 1 Nm^3 of biogas is combusted and the water vapour formed in the combustion is condensed. The **lower heating value** (LHV) shows the energy formed when the water vapour is still not condensed. A typical value of LHV of biogas from anaerobic digestion is 18,4 MJ/m^3 at 20 ºC compared to methane that results in 33,4 MJ/m^3 [34].

The **Wobbe index** or Wobbe number is defined as the heating value (lower or higher, MJ/Nm^3) divided by the square root of the relative density of the fuel gas compared with air.
The Wobbe index is primarily used to evaluate the interchangeability of fuel gases with respect to equal heat input rate and fluid handling capability of burners, piping, valves, controls etc. It is a measurement for the combustion behaviour and may not deviate from a desired range.
The minimum amount of CH_4 required as well as the maximum N_2 depends on this index. However, in some cases the upgraded gas may not have to meet the pipeline specifications completely. For example, if the Wobbe index of the natural gas is higher than the minimum limit, the mixture of natural gas and upgraded gas can meet this specification even if the Wobbe index of the upgraded gas is lower than the limit. If lower qualities can be allowed as output from the upgrading process, the investment and operating costs can be reduced.

In Europe only two kinds of natural gas are distributed. These kinds are indicated with L and H; the L gases originate only from the Dutch natural gas from the Groningen gas fields with high content of nitrogen (Wobbe index = 38-47 MJ/m^3), while nearly all other natural gases in

Europe are within the H quality limits (46-57 MJ/m^3). Locally there are often stricter requirements on the Wobbe number.

In Figure 6, Biogasmax project[2] [9] proposes a series of values for a European technical specification on parameters defining biomethane quality. It should be noted that:

- This proposal has been built on the basis of the numerous experiences regarding biomethane grid injection throughout Europe. The frequency of measurement of such quality parameters will be discussed as part of the contract between biomethane producer and grid operator.
- These values need to be considered as tentative figures. They may consequently evolve according further experiences and oncoming lessons learnt from current practices.
- All kind of feedstocks (used as substrates for biogas production) are concerned by this proposal: biowaste, garden waste, manure, sewage sludge, energy crop, landfill, etc.
- Flexibility to the local/regional/national grid operators has to be ensured; grid operator will define case by case whether biomethane producer has to measure these parameters or not. This will depend on the feedstock used (for instance, the measurement of biomethane produced from source-separated collected biowaste involves less parameters than biomethane produced from landfills, as the latter deals with more minor pollutants). The kind of upgrading technology used has also to be taken into account. Such flexibility will consequently allow the biomethane producer to meet the grid operator's requirements in an easier way.
- Biomethane producer has to warranty the feedstock origin to the grid operator.

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[2] BIOGASMAX was funded by the European Commission's 6th Frame Programme FP on Research & Development. There were 30 partners from seven European countries involved in Biogasmax between 2006 and 2010. The project aims to help the European Community in reducing dependency on oil and reducing greenhouse gas emissions through increased use of biomethane in the transport sector generated from a wide variety of feedstock available in urban areas and regions in Europe. Since 2006, Biogasmax has adopted the well-to-wheel approach: using the entire chain of biomethane from waste collection to use in vehicles, recovery of organic matter in agriculture; and the essential steps of upgrading, distributing and transporting.
It has four major objectives:
1. Demonstrate large scale digestion and biogas upgrading units, producing biogas from waste material available from the urban and close by rural areas;
2. Demonstrate the expansion of gas-driven fleets in public and private transport, for example buses, waste collection trucks, and service cars;
3. Prove the technical reliability, cost-effectiveness, environmental and social benefits of biogas fuels;
4. Widely spread knowledge of results gained in the demonstration projects among other European cities and stakeholders by information and training materials, lectures and conferences, with particular emphasis on new Member States. [9]

Common parameters (all types of biomethane)				
Parameter	**Unit**	**L-Gas**	**H-Gas**	**Comments**
Wobbe Index (range) $W_{S,n}$	kWh/m³	10.86 – 12.44	12.69 – 15.19	Range of Gross Wobbe Index at **15°C and 1013.25 mbar** as mentioned in standard EN 437. Propane addition is allowed to reach the required range
	MJ/m³	39.1 – 44.8	45.7 – 54.7	
Heating value (range) $H_{S,n}$	kWh/Nm³	8.4 – 13.1		Range of current SPECs in Europe
	MJ/Nm³	30.2 – 47.2		Range of current SPECs in Europe
Relative density d_n	-	0.55 – 0.75		Range of current SPECs in Europe
CO_2	Vol.-%	≤ 11	≤ 6	Range of current SPECs in Europe
Hydrocarbons (without CH_4): condensation point	°C	Soil temperature (related to grid pressure of connected grid)		To be measured only when heating value is enhanced by adding hydrocarbons (propane)
Water dew point	°C	Soil temperature		Related to grid pressure of connected grid
Dust	-	Technically free		
O_2	%	≤ 3		Range of current SPECs in Europe
Sulphur (total)	mgS/Nm³	≤ 30		Odorant included
THT	mg/Nm³	15-40		Range of current SPECs in Europe
H_2S	mg/Nm³	≤ 5		Range of current SPECs in Europe
H_2	Vol.-%	≤ 10		Range of current SPECs in Europe : <5. Nevertheless, H_2 threshold value has to be enhanced to allow biomethane from gasification
NH_3	mg/Nm³	≤ 3 - 20		Range of current SPECs in Europe
Additional parameters (depending on specific substrates) (Based on current range applied in Europe)				
Parameter	**Unit**			**Considered feedstock**
Organic silicon compounds (calculated as Si)	mg/Nm³	≤ 10		landfill, sewage sludge
F	mg/Nm³	≤ 10 - 25		landfill, sewage sludge
Cl	mg/Nm³	≤ 1 - 50		landfill, sewage sludge
Hg	µg/Nm³	≤ 1		landfill

Figure 6 – Parameters defined by BIOGASMAX project for biomethane[3] [9]

3.5.3.1 Pressure Swing Adsorption (PSA)

Since the development of the process in the 1960s, PSA has become one of the most widely used industrial gas separation technologies, primarily as a result of its flexibility, low capital cost and efficiency [54].

PSA processes are based on the property of porous adsorbent materials to selectively retain components under high pressure, according to molecular size.

In case of biogas, methane (molecular size of 2,18 A) is allowed to pass through interstitial spaces of the adsorbent while CO_2 (2,3 A) is retained into the matrix. The adsorbed

[3] In the figure, *Heating value* is HHV

component of the gas steam is then desorbed by reducing the pressure, allowing therefore the regeneration of the adsorbent material.

Adsorbent materials being utilised and developed include activated carbon, natural zeolites (alumina silicates), synthetic zeolites, activated alumina, silica gels and polymeric sorbents. Adsorbents are packed into columns which are arranged in sequence according to the input and the output gas contents [54].

When high concentrations of H_2S are present in the raw biogas, initial removal-reduction is required because these molecules can not be desorbed and thus the adsorption material is poisoned.

The upgrading system usually consists of four vessels. Each vessel operated in alternating cycle of phases. During adsorption phase, biogas enters from the bottom into one of the vessels. Before the adsorbent material is completely saturated, the adsorption phase is stopped and another adsorber vessel that has been regenerated is switched into adsorption mode to achieve continuous operation.

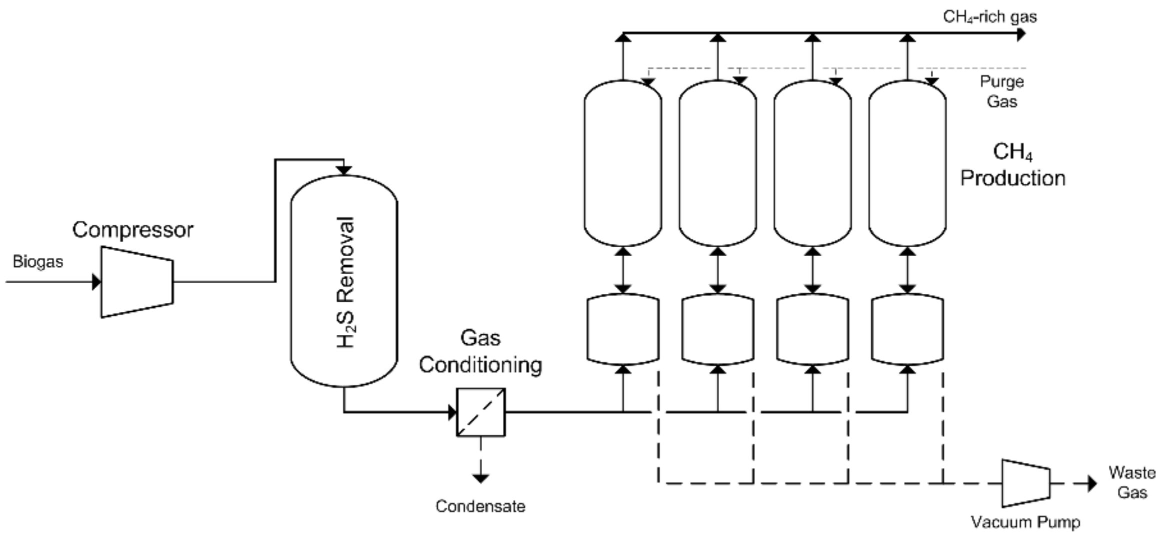


Figure 7 – Pressure Swing Adsorption [21]

Regeneration is performed in two steps. Initially, the pressure is reduced by a pressure balance with an already regenerated adsorber vessel. This is followed by a second depressurization step to almost atmospheric pressure. The gas leaving the vessel during this step contains significant amounts of CH_4 and is recycled to the gas inlet. These significant amounts of CH_4 were trapped within the voids of the adsorbent particles. Before the adsorption phase starts again, the adsorber vessel is repressurized stepwise to the final adsorption pressure. A full cycle is completed in approximately 3-5 minutes. The lifetime of the adsorbent material is taken to be 3 or 4 years [21].

The waste stream of the PSA-plant consists of N_2, O_2, H_2O, H_2S and CO_2, depending on biogas composition. Also some significant amounts of CH_4 are found: is therefore recommended to burn the stream [21].

3.5.3.2 Absorption

- **Water scrubbing (PWS)**

This method relies on the principle that CO_2, and also H_2S, are more soluble in water than CH_4. Raw biogas is pressurized and introduced to the bottom of a scrubbing tower, while water is flushed into the top. This high pressure increases the dissolubility of gases in water. The tower is fulfilled with packing material with a high surface area media to provide high contact area between water and gas. As the raw gas moves up the column against water, CO_2 and H_2S dissolve and the upgraded gas leaves the top of the tower. Any methane dissolved within the water is captured by depressurizing the water in the release tank: gases return to the bottom of the column. In the stripper the washing water is regenerated and CO_2 and H_2S are stripped by air [54].

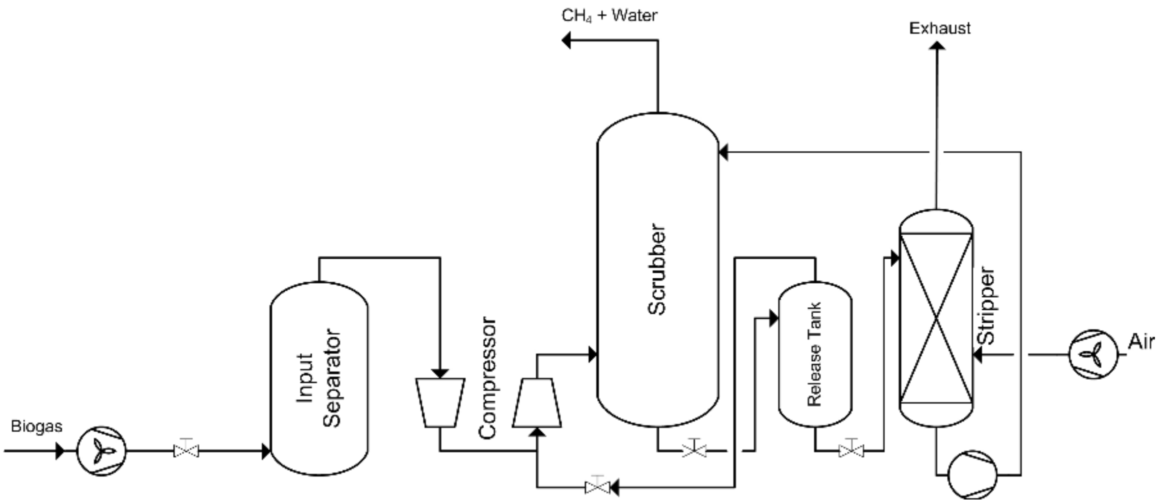


Figure 8 – Water scrubbing [21]

After a drying step, the obtained CH_4 purity can reach 98% using this process and yields can achieved up to 94%. The remaining 6% is the methane in the water that can not be recovered.

In *single pass scrubbing*, the washing water is used only once, so no contamination in the water occurs and the absorption efficiency is at its maximum. The disadvantage of this method is that it requires a large amount of water. Thus it is used only in wastewater plants from which water can be received. Otherwise, *Regenerative absorption* is preferred [21].

The mass transfer from the gas phase to the water phase occurs when there is a difference between the concentrations.

The advantage of working at high pressure is explained by Henry's Law:

$$P_i = H \cdot C_{max}$$

C_{max} = saturation concentration of the component [mol/m^3]

H = Henry's coefficient [Pa·m^3/mol]

P_i = Partial pressure of the component [Pa]

According to Dalton's law, the total pressure is the sum of all partial pressures. Increasing the total pressure of the mixing makes the saturation concentration rise. However, over 20 bars the dissolubility will no longer increase linearly with the pressure.

Working at high pressure results in lower required amount of water and in a faster regenerating process because its driving force is the difference in gaseous concentration between the oversaturated water and the equilibrium conditions.

Another important factor is the pH: when pH decreases, CO_2 and H_2S will dissolve less. However, at high pH sulphur and carbonate ions will precipitate. It is best to work at a pH of 7.

Water scrubbing technologies have advantages since they can work at high temperatures and moisture rates, with corrosive gases and particulate matter.

The air used to strip the regenerated water has a high percentage of CO_2 and traces of H_2S and CH_4. It is recommended to treat this stream to remove H_2S and then to burn the CH_4 content [21].

- **PHYSICAL ABSORPTION (ORGANIC SCRUBBING)**

The process is similar to water scrubbing, but a non-reactive fluid is used to physically absorb the unwanted components as it can dissolve significantly more CO_2 per unit of volume than water, leading to smaller volumes and plant sizes. Spent absorbents are then regenerated by depressurizing and/or heating.

Solexol and Genosorb are the names of the organic solutions available in the European market.

- **CHEMICAL ABSORPTION (AMINE SCRUBBING)**

A further variation on scrubbing technology is to use amine-based chemicals as the solvent such as monoethanolamines, dimethilethanolamines and diglycolamines.

The reactions that occur between the aqueous solution and CO_2 are the following [21]:

10) $2RNH_2 + CO_2 \leftrightarrow RNHCOO^- + RNH_3^+$

11) $CO_2 + OH^- \leftrightarrow HCO_3^-$

12) $RNH_3^+ \leftrightarrow RNH_2 + H^+$

13) $H_2O \leftrightarrow H^+ + OH^-$

Reaction 10) gives the most significant contribution to the conversion of CO_2, while reaction 11) is less important because pH is low and not much OH^- are present in the solution. Since OH^- ions are in equilibrium with the amine molecules, also reactions 12) and 13) have to be taken into account.

Amine scrubbing is also effective at lower pressures compared to water and organic scrubbing leading to reduced compression energy requirement. However, some heat is required to regenerate the amine solution prior to recirculation [54].

The only process stream next to biogas needed in the absorption process is a liquid water phase in which amines are dissolved. As can be seen in Figure 9, the biogas flows through a column filled with the amine solution. In this column, the CO_2 is split from the biogas and the biogas leaves the absorption column. The amine solution including the captured CO_2 leaves the column and is generated in the regeneration column. During this process, the CO_2 is split off and is emitted in the atmosphere as a waste stream. The amine solution will flow back into the column to capture CO_2 again. This solution must be replaced a few times a year and then it becomes a waste stream too: it can be separated into a water phase and the amines using a membrane. The clean water phase can then be purged to a river. The only real waste streams are the CO_2 stream and the amines [21].

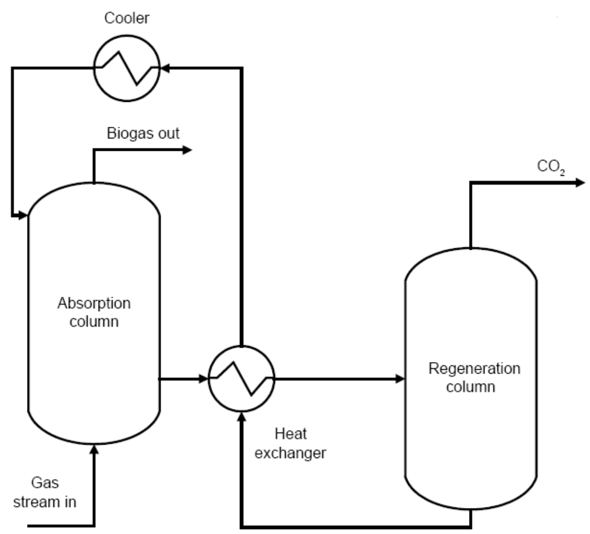


Figure 9 – Chemical absorption [21]

3.5.3.3 Membrane separation

Membrane separation relies on the preferential transfer of one gas from a mixture through a semi-permeable membrane, while other components are retained.

High pressure membrane has gases present on each side of the membrane; if a pressure differential is set up on an opposing site or a polymeric film, permeation across the film will occur. Small molecules and high soluble molecules permeate easily, and this happens to CO_2.

Each polymer or copolymer membrane in the form of a flat film or a hollow fibre can separate gases. For example, cellulose acetate membrane is used because it is inert and stable dealing with CO_2 and hydrocarbons. Overall, the efficiency of the process depends on the membrane used, and the choice is linked to this factors: the selectivity towards the gases, membrane permeability, lifetime, operational temperature and humidity range, maintenance and replacement costs [21].

The total energy required is low because the membrane is passive; membranes can last from 10 to 15 years but they are expensive and fragile [21].

Biogas is generally upgraded in a multiple stage process to achieve a higher methane yield [54].

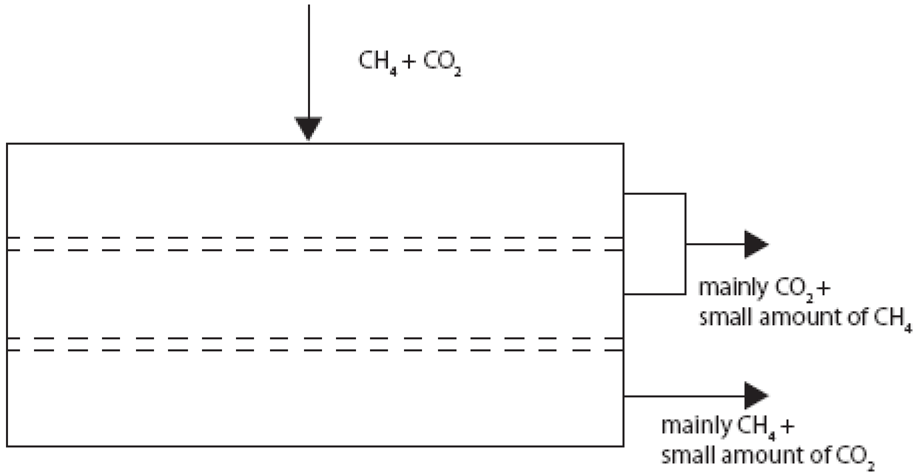


Figure 10 – Membrane separation [21]

Waste gas from the final stage has a high percentage of methane and must therefore be flared or used for heat or captured catalytically [54].

H_2S content depends on the choice of membrane. Either the input stream or the output stream can be cleaned. There are two options:

- to remove H_2S from the input stream with a pre-treatment;
- to remove H_2S from the rich-methane gas flow: however, the waste stream can be burned because it is cheaper to maintain an engine rather than to clean the whole biogas [21].

Low pressure membrane works at atmospheric pressure and has a liquid adsorbent (such as heat regenerative amine solution) on one side of the hydrophobic membrane. The process can also provide a high purity CO_2 that can be sold as a product [54].

3.5.3.4 Cryogenic technique

Different constituents of a mixture have different boiling points: methane has a boiling point of -160 °C, CO_2 of -78 °C. Therefore, by progressively cooling the raw gas under pressure, the constituents can be separated. First, the gas is compressed, then it is cooled with heat exchangers and finally it is expanded to condensate the target contaminant. The process can also provide a high purity CO_2 that can be sold as a product [54].

This kind of technology is used only in few experimental devices [57].

3.5.3.5 Comparisons

No LCA study comparing the different upgrading technologies was found in literature. In different LCA studies, a default percentage of leakage is taken to consider the average of the methods.

Berglund [7] states that the loss of CH_4 during upgrading of biogas is normally assumed to be less than 2% of the biogas produced, but may vary between 0,2-4%, even up to 11-13%.

Poeschl et al. [59] consider 3% of methane loss.

Table 6 represents the most important parameter that IEA [57] assumes, considering manufacturers, pilot plants and literature information.

Parameter	PSA	Water scrubbing	Organic physical scrubbing	Chemical scrubbing
Pre-cleaning needed[a]	Yes	No	No	Yes
Working pressure (bar)	4–7	4–7	4–7	No pressure
Methane loss[b]	<3 % / 6–10 %[f]	<1 % / <2 %[g]	2–4 %	<0.1 %
Methane content in upgraded gas[c]	>96 %	>97 %	>96 %	> 99 %
Electricity consumption[d] (kWh/Nm^3)	0.25	<0.25	0.24–0.33	<0.15
Heat requirement (°C)	No	No	55–80	160
Controllability compared to nominal load	+/- 10–15 %	50–100 %	10–100 %	50–100 %
References[e]	>20	>20	2	3

Table 6 – Comparison between selected parameters for common upgrading processes [57]

The most important point for methane emissions from the upgrading plant is the off-gas. Optimally the off-gas consists of only carbon dioxide, but generally it also contains methane in varying concentrations. This amount depends on the physical principle that allows for the removal of carbon dioxide.

In water scrubbing and in physical and chemical absorption, methane leakage is due to the fact that also CH_4 has solubility in the solvent, even if it is negligible compared to CO_2, and then it is released in the atmosphere during the regeneration phase of the reagent. In general, the higher is the work pressure, the higher is the methane loss.

In PSA technology, losses are due to the little affinity between activated carbon and methane that is released during the regeneration of the column.

To enable a systematic approach for both quantification of methane emissions and for minimisation of them, the Swedish system for methane emission control from biogas production plants and biogas upgrading biogas plants, called the Voluntary Agreement [41], was initiated in 2007. 26 upgrading plants joined the Voluntary Agreement.

For the upgrading plants, measurements start when the gas enters the building containing the upgrading equipment and end when the gas is cleaned, dried and odorized. Methane emissions during transport of the upgraded biogas, compression, propane addition, gas storage or emissions at filling stations are not included. In Figure 11 methane emissions are represented for three different types of upgrading technologies: chemical scrubber, PSA (Pressure Swing Adsorption) and water scrubber. The red line marks 2% methane loss which was often guaranteed by the plant manufacturers.

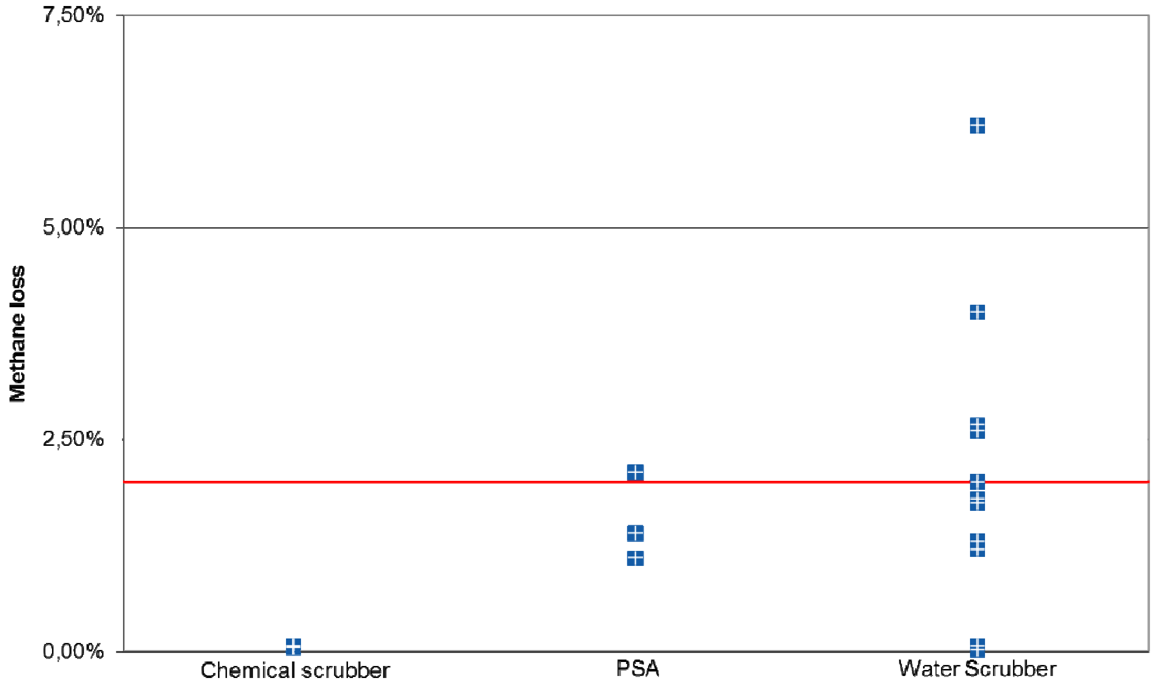


Figure 11 – Total methane losses for the plants participating to Voluntary Agreement [41]

It is shown that often methane leakages do not respect manufacturers' definitions. It is important to be aware that also better or worse situations can occur.

To lower the methane slip the off gas is at some plants treated to break down methane by e.g. catalytic burning or flaring.

3.6 THE EUROPEAN CONTEXT AND THE FUTURE PERSPECTIVES

The biogas sector is gradually showing its core activities as waste treatment and energy production: 8.7 Mtoe of primary biogas energy were produced in 2010 in EU [28].
25.2 TWh (2.2 Mtoe) of biogas electricity, which represents an increase of 17.9% on 2008, were produced mainly in digestion plants (53.4%), followed by landfills (37.2%) and water treatment plants (9.4%). Cogeneration increasingly plants produce electricity and, at the same time, also supply heat. Heat production was 173.8 ktoe in 2009, which is 8.3% up on 2008. This figure only includes the heat sold to heating networks, no heating that is used in the process itself and in the farm is considered [2].
The other type of biogas utilisation, biomethane upgrading and injection (purified biogas) into the natural gas grid or utilisation for transport, is booming in a number of countries, such as Sweden, Germany and the Netherlands [28].

Table 7 reports the primary production of biogas in Europe referred to 2009 [2]. Figure 12 better shows the importance of the agricultural sector over the total production of biogas in Eu-25. Figure 13 represents the subdivision of the upgrading technologies used to treat biogas coming from agricultural digestion plants.

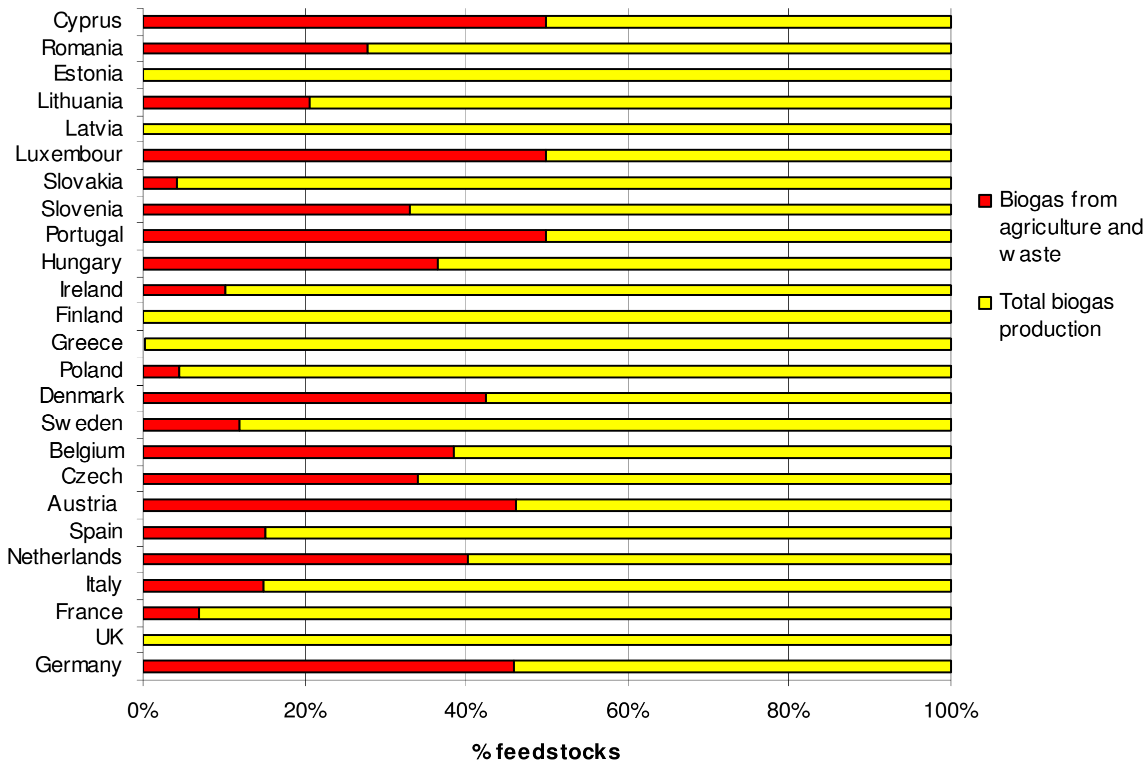


Figure 12- Biogas production in EU-25, different feedstocks [2]

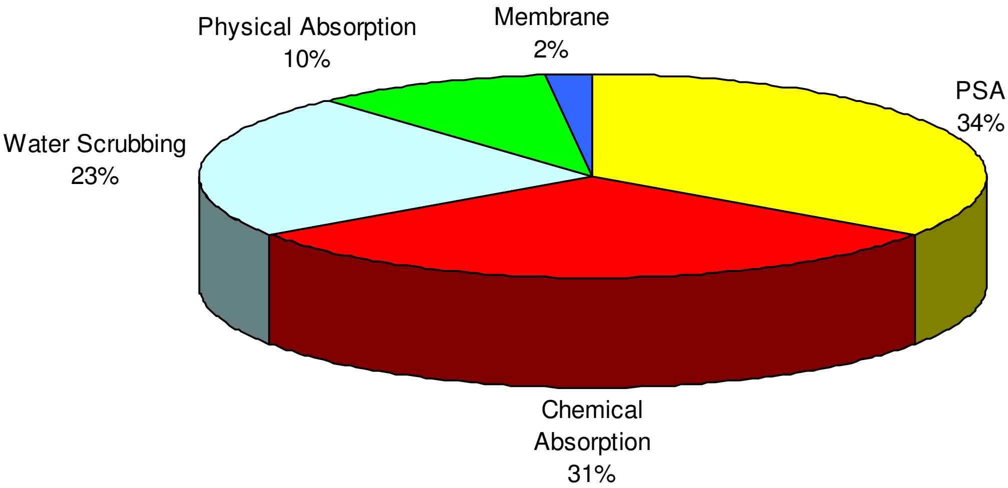


Figure 13 – Different upgrading technologies in EU-25 for biogas in the agricultural sector [57]

Countries	Landfill gas	Sewage sludge	Other biogas	TOTAL
EU-25	3001,5	1003,5	**4340,7**	8345,7
Germany	265,5	386,7	**3561,2**	4213,4
UK	1474,4	249,5	**0**	1723,9
France	442,3	45,2	**38,7**	526,2
Italy	361,8	5	**77,5**	444,3
Netherlands	39,2	48,9	**179,8**	267,9
Spain	140,9	10	**32,9**	183,8
Austria	4,9	18,9	**141,2**	165
Czech Republic	29,2	33,7	**67**	129,9
Belgium	44,3	2,1	**78,2**	124,6
Sweden	34,5	60	**14,7**	109,2
Denmark	6,2	20	**73,4**	99,6
Poland	35,5	58	**4,5**	98
Greece	46,3	12,2	**0,2**	58,7
Finland	30,6	10,7	**0**	41,3
Ireland	23,6	8,1	**4,1**	35,8
Hungary	2,8	10,3	**17,5**	30,6
Portugal	0	0	**23,8**	23,8
Slovenia	8,3	3	**11**	22,3
Slovakia	0,8	14,8	**0,7**	16,3
Luxembourg	0	0	**12,3**	12,3
Latvia	7	2,7	**0**	9,7
Lithuania	1,3	2,1	**1,2**	4,6
Estonia	2	0,9	**0**	2,9
Romania	0,1	0,7	**0,5**	1,3
Cyprus	0	0	**0,2**	0,2

Table 7 - Primary production of biogas in the EU 25 in 2009 (ktoe) [2]

Germany has opted to develop agricultural digestion plants by encouraging the planting of energy crops. As a result of this strategy, Germany is the leading European biogas producer, alone accounting for half of European primary energy output (50.5% in 2009) and half of biogas-sourced electricity output (49.9% in 2009) [2]. According to the German biogas association (Fachverband Biogas e.V.), the country has 4984 biogas plants, 1093 of which were installed in 2009, with 1893 MW of electrical capacity. This exceptionally lively performance is due to the implementation of a feed-in tariff that combines a number of premiums [28].

In 2009 **Italy** became the number four biogas producer in Europe with 444.3 ktoe, as primary energy production increased by 8.4% over 2008 and electricity production by 8.8%. There are now about 200 installations with combined capacity of about 200 MW_{el}, and at least 2000 MW_{el} is planned in the next 5 years. The implementation of highly pro-active legislation geared to agricultural biogas development is responsible for this bright outlook [28].

The **United Kingdom** prefers to rely on energy recovery from landfill biogas. According to the DECC (Department of Energy and Climate Change), the country produced 1723.9 ktoe of biogas in 2009 of which 1474.4 ktoe was landfill biogas (85.5%). This type of biogas took full advantage of the British green certificates system. The reason for the high interest in this deposit is that the British system is biased in favour of the most cost-effective sectors and landfill biogas production costs are lower than for the other renewable sectors [28].

In **France**, most of the energy produced (526.2 ktoe in 2009) comes from biogas trapped directly in non-hazardous waste landfills repositories (84% of the total) and for the most part this deposit is still under-exploited. So in 2009, biogas electricity output production was only 846.4 GWh. The unattractive feed-in tariff is the reason for the under-exploitation [28].

The situation in **Ireland** is particularly interesting. Grass is the Irish most common agricultural crop, covering 91% of agricultural land and 57% of the total land area. There are two main agricultural land uses in Ireland, grassland and arable, both of which could be used for grass biomethane. However, as Ireland is only around 80% self-sufficient in cereals, the use of arable land for grass biomethane production would have a direct impact on the country's food supplies and is therefore not recommended. Grassland in Ireland is used mainly for beef, dairy and sheep farming, and all three sectors have high levels of self sufficiency. Therefore, a diversion of grassland to biomethane production could take place without having a direct impact on food supplies in this country. A grass biomethane industry should therefore be based in areas with high grassland coverage [69].

AEBIOM [2] assumes that 25 Mha agricultural lands (arable land and green land) can be used for energy in 2020 without harming the food production and the national environment. This land will be needed to produce raw materials for the first generation fuels, for heat, power and second generation fuels and for biogas crops. In the following scenario, 15 Mha land is used for first generation biofuels (wheat, rape, sugar beet, etc.), 5 Mha for short rotation forests, miscanthus and other solid biomass production and 5 Mha for biogas crops On this basis the potential for biogas in 2020 for the EU 27 is estimated as follows:

Origin(according to template for National Renewable Energy Action Plans)	Potential Billion m³ Biomethane	2020		
		Assumed percentage of use until 2020	Primary energy Billion m³ Biomethane	Primary energy Mtoe
Agriculture	**58,9**	**62%**	**36,4**	**31,3**
Agricultural crops directly provided for energy generation (5% of arable land; calculation in annex)	27,2	100%	27,2	23,4
Agricultural by-products / processed residues	31,7	28%	9,2	7,9
straw	10,0	5%	0,5	0,4
Manure	20,5	35%	7,2	6,0
rest (landscape management)	1,2	40%	0,5	0,4
Waste	**19,0**	**50%**	**9,5**	**8,2**
Biodegradable fraction of municipal solid waste including biowaste (biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises, and comparable waste from food processing plants) and landfill gas	10,0	40%	4,0	3,4
Biodegradable fraction of industrial waste (including paper, cardboard, pallets)	3,0	50%	1,5	1,3
Sewage sludge	6,0	66%	4,0	3,4
Total	**77,9**	**59%**	**45,9**	**39,5**
The realistic potential of methane derived from animal manure and energy crops and waste lies in the range of 40 Mtoe in 2020 as compared to a production of 5,9 Mtoe in 2007. The use of catch crops for biogas production was not considered in the calculation and offers an additional potential.				

Table 8 – Estimation of biogas potential for EU-27 in 2020 [2]

Most of the European Union countries have drawn up a biogas roadmap as part of their national renewable energy action plan. These plans have been developed under the framework of the European Renewable Energy Directive (2009/20/EC). The ECN (Energy Research Centre of the Netherlands) has compiled all the data extracted from the 26 (out of 27) NREAP (National Renewable Energy Action Plan) documents sent to the European Commission on 13 December 2010 on behalf of a study funded by the EEA (European Environment Agency). The study's findings show that the European Union will increase electricity production from biogas to 63.3 TWh in 2020 (with Germany contributing 23.4 TWh). The production of recovered heat, both sold and unsold, will rise from to 5 Mtoe [28].

4

DESCRIPTION OF THE WORK: LCA

"Science is facts; just as houses are made of stones, so is science made of facts; but a pile of stones is not a house and a collection of facts is not necessary science"

Henry Pointcaré, Science and Hypothesis (1901)

In this Chapter, the LCA of biogas production and utilisation is explained, focusing on the different phases of the Life Cycle Assessment.

Paragraph 4.1 introduces the definition of the goal and the scope with the main assumption made in the all study.
In Paragraph 4.2 the processes commonly used in all the pathways are explained.
In Paragraph 4.3 each pathway is represented with the specific data collection.
Finally, the results of the sensitivity analysis focusing on the uncertainty of this study are evaluated in Paragraph 4.4.

4.1 DEFINITION OF GOAL AND SCOPE

4.1.1 Goal definition

The goal of this study is to analyse the environmental performances from cradle to grave of different biogas production (from grass, maize, manure and from co-digestion of the last two) and utilisation (in a combined heat and power engine or as biomethane) scenarios.

This work is an example of micro-level, process-related decision support study. Its purpose is the evaluation of the sustainability of the production of energy (thermal energy or electricity) from biomass, in order to support the investigations of the staff of the JRC of the European Commission that is involved in calculating the emissions of GHG from this biofuel, as already expressed in the introduction of this work. Other LCA studies have been reported in the same section.

The main assumptions will be fully explained in the next Paragraphs, while showing each process that is part of biogas systems. The necessity of formulating hypothesis is due to the lack of data and to the requirement to represent the whole European context: this is the reason why the collection of new information is one of the scopes of this work.

In Table 9 the most significant parameters, that are assumed to be valid for each biogas pathway, are listed with their references.

	Amount	Unit	Reference	Comment
Methane content in biogas	0,55	$\frac{Nm^3 CH_4}{Nm^3_{biogas}}$	15	
Carbon dioxide content in biogas	0,45	$\frac{Nm^3 CO_2}{Nm^3_{biogas}}$	15	
Hydrogen sulphide content in biogas	80	ppm	49	
Density methane	0,717	$\frac{kgCH_4}{Nm^3 CH_4}$	74	
	0,668	$\frac{kgCH_4}{m^3 CH_4}$	Calculated	At 20℃
LHV methane	50	$\frac{MJCH_4}{kgCH_4}$	34	
	33,4	$\frac{MJCH_4}{m^3 CH_4}$	Calculated	At 20℃
Density biogas	1,28	$\frac{kg_{biogas}}{m^3_{biogas}}$	Calculated	At 20℃
LHV biogas	18,37	$\frac{MJ}{m^3}$	Calculated	At 20℃

Table 9 – Parameters valid for this study

4.1.1.1 An important goal: the inventory of the emissions of CH_4, N_2O, NH_3

An important goal of the study is the inventory of the emissions of gases linked to leakages of biogas or emissions from feedstocks or products such as manure or digestate. The most important gases evaluated are methane, nitrous oxide and ammonia.

Among the feedstocks, it is interesting to understand the effects of manure management as a direct and indirect source of gas emissions: manure contains substantial quantities of N, much of which is in inorganic forms, C and water, that are three essential factors controlling the processes leading to production and emissions of N_2O and CH_4. Therefore, the management practice selected by farmers has the scope to influence the magnitude of gaseous losses, and the potential to reduce those emissions. There is the potential for N_2O and CH_4 emissions at each stage of manure management.

We consider two different kinds of manure management:

- storing and spreading manure as raw material
- digesting manure and storing and spreading of its digestate.

The digestate resulting from anaerobic digestion of energy crops (or manure + energy crops) is supposed to emit the same typology of gases as manure digestate. However, different amounts are calculated according to the composition of the digestate that is supposed to be linked to the composition of the feedstock.

Methane (CH_4) is a greenhouse gas with a Global Warming Potential 25 times higher than carbon dioxide [44].

Losses of CH_4 affect the environmental performance of the system studied in two ways:

- they increase the emission of GHG;
- they increase all fuel-cycle emissions in proportion to the losses since the emissions are expressed per MJ of energy service. For example, if the loss is higher it is necessary to cultivate more feedstock mass in order to supply the methane lost and to provide the same amount of energy [7].

Methane is released in the atmosphere during anaerobic digestion (as a leakage from the digester), in the open storage tank of digestate, in spreading the digestate, in CHP combustion and in the phase of upgrading. Undigested manure emits methane as well, both in the storage phase and in spreading. Slurry stores are sources of CH_4 emissions as the anaerobic environment favours methanogenesis. Emissions of CH_4 generally occur immediately after manure application to land. These emissions are usually short-lived, as methanogenesis is sensitive to O_2 and diffusion of O_2 into the manure on the soil surface inhibits CH_4 formation [17].

Nitrous oxide (N_2O), also called laughing gas, has a GWP_{100} of 298 [44].

In details, leakages in the atmosphere are found in an open storage tank of digestate and manure, and during the spreading on the fields.

As far as *spreading* concerns, we assume to consider two different sources of N_2O.

An amount of N_2O is emitted immediately after (and during) spreading and is generally the result of a source of NO^{3-} within the manure or the effect of manure carbon fuelling denitrification of residual soil nitrate [17].

The second contribution comes from long term emissions of nitrous oxide that are generated by nitrification and denitrification which occur in soil following addition of raw manure or digestate, as shown in Figure 14. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas N_2. Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. The majority of inorganic N present in slurry and fresh manure is in the form of ammonium.

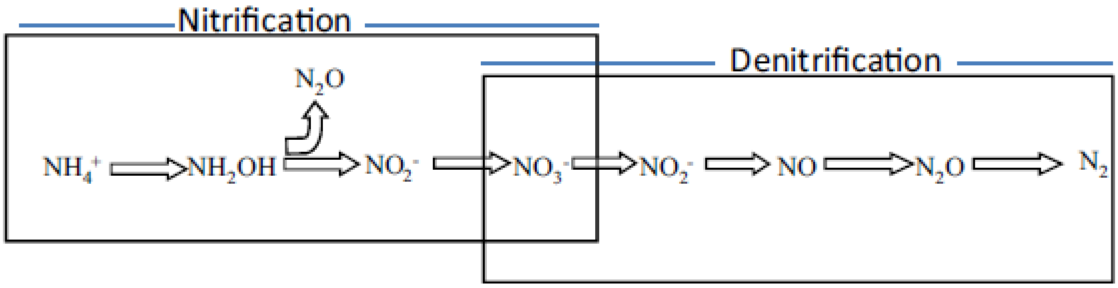


Figure 14 - Schematic chemical representation of two processes responsible for N_2O production [17]

IPCC [22] gives a detailed methodology to estimate N_2O emissions of human-induced net N additions to soils (e.g., synthetic or organic fertilisers, deposited manure, crop residues, sewage sludge), or of mineralisation of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils (e.g., Forest Land/Grassland/Settlements converted to Cropland).

The emissions of N_2O that result from anthropogenic N inputs or N mineralisation occur through both a direct pathway and through two indirect pathways.

- *Direct emissions:* in most soils, an increase in available N enhances nitrification and denitrification rates which then increase the production of N_2O. Increases in available N can occur through human-induced N additions or change of land-use. Source of nitrogen are: synthetic N fertilisers, organic nitrogen applied as fertiliser (e.g. animal manure, compost, sewage sludge, rendering waste), N in crop residues left on the field, N mineralisation associated with land use change, drainage/management of organic soil.

Hence, it may not contribute too much to short and medium term N_2O emissions. Also, large quantities of N are emitted via NH_3 volatilisation within 48 h following manure spreading, thus reducing the pool of N available for N_2O emission.

Direct emissions are estimated with IPCC [22] Tier 1 equations.

- *Indirect emissions:* N_2O is also emitted after the volatilisation of NH_3 and NO_x from managed soils and from fossil fuel combustion and biomass burning, and the subsequent re-deposition of these gases and their products NH_4^+ and NO_3^- to soils and waters;

Another indirect emission occurs after leaching and runoff of N, mainly as NO_3^-, from managed soils.

Again, Tier 1 equation [22] is applied.

Anaerobic digestion removes organic matter and affects infiltration of manure slurry and the content of volatile solids in the soil slurry mixture. Reducing VS decreases the risk of N_2O emissions, as the microbial demand for O_2 and consequently heterotrophic denitrification is lower. Some researchers have reported lower N_2O emissions from soils amended with digested slurries than from untreated slurries, but this result has not been consistent suggesting that application conditions and soils properties may influence effects of digested slurries on N_2O emissions [17].

Considering the *storage*, if the slurry/faeces/urine remains in a predominantly anaerobic state with slight opportunity for the NH_4^+ to be nitrified, little or no N_2O emissions are likely to occur from such systems.

Anthropogenic **ammonia** mainly originates in Europe from agriculture (livestock production). About 25% of the nitrogen in animal excretion is lost to the atmosphere in Western Europe. Several factors have an influence on the ammonia release in slurry management: nitrogen content, pH- value, urease activity, C/N ratio, availability of oxygen and temperature of manure and air, adsorption of ammonia nitrogen, sizes of manure surface areas, air movements and ventilation rates.

In particular, ammonia emissions from slurry storage will be influenced by the surface area to volume ratio of the store. The emissions following the application of manure to land are influenced by the proportion of the manure directly exposed as an emitting surface, the duration of that exposure and the weather conditions over that duration. For slurries, one of the key controlling parameters is the dry matter content which, together with soil characteristics, can determine the rate and extent of slurry infiltration into the soil. Wind speed, temperature (or solar radiation) and rainfall are important weather factors influencing emission from slurry applications together with application rate and crop and soil characteristics at the time of application [70].

4.1.2 Definition of scope: what to analyse and how

4.1.2.1 Pathways, functional unit, reference system

In this study, different pathways are analysed. Each pathway is the combination of different technologies or possible solutions linked to the supply of the feedstock, the utilisation of the biogas and the management of the digestate. Table 10 shows in details the pathways that are created and analysed.

Feedstocks:

- Energy crop: maize silage
- Energy crop: grass silage
- Manure
- Co-digestion of maize silage and manure

In this work, only the digestion of energy crops and manure is considered because they are the most common agricultural resources used as feedstocks.

Management of the digestate:

- Stored in an open tank
- Stored in a closed tank

Utilisation of biogas:

- Combustion in a CHP device for the production of heat and power
- Upgrading to a methane-rich gas, injection into the gas grid and combustion in a domestic boiler for the production of heat. The upgrading system can be PSA, PWS, Chemical absorption or Physical absorption.

The functional unit of the systems refers to the final product of the chain considered (**output-related functional unit**). Therefore, it depends on the utilization of the biogas.
In the pathways regarding CHP devices, the functional unit is **1 MJ of electricity**.
Concerning the production of biomethane, its injection into the grid and the utilisation in a domestic apparatus, the functional unit is **1 MJ of heat**.

The same functional unit, that is different according to the utilisation of the biogas, is valid for the **reference system**, the selection of which can strongly affect the results of the study. Ideally, the bioenergy system should be evaluated against the energy system most likely to be displaced (the “marginal” system). Since in real life it is difficult to know which energy source will be replaced, instead the option chosen in this work is to estimate the emissions savings comparing the bioenergy system to the average energy system representing the current European mix of resources.

In addition, the study should consider what would have happened to the same biomass in the reference case, when a traditional fuel is the energy source. This changes according to the feedstock used.

Concerning energy crops, *land use change* should be evaluated. Direct land use change (dLUC) is a variation in the soil occupation to produce biomass for bioenergy (for example, if in the reference system the land is occupied with a different cultivation) [10]. Energy crops are supposed to be cultivated for fodder production in the reference system: it means that the soil does not change its occupation and no direct land use change emissions should be accounted for in the reference system. Indirect land use change (iLUC) refers to variations in soil occupation that occur outside the system boundary due to the displacement of services that were previously provided on the land now used for bioenergy [10]. In this case, fodder is supposed to be produced in an additional land previously not occupied, causing emissions. However, quantifying these emissions is difficult because it is necessary to consider complex trends and interactions between and inside different sectors. For that reason, iLUC is not taken into account in this study.

As far as manure is concerned, if this residue is not anaerobically digested it is generally firstly stored in an open tank and then spread on fields as organic fertiliser, causing emissions. Hence in the reference system the emissions due to undigested manure management should be added to the ones derived from the energy production. An alternative way to consider these emissions is to refer to them as avoided emissions in the biogas system. It consists in subtracting the amount of the gas emitted in the biogas system, considering as a result the net emissions: it is said that the biomass system benefits of *credits*.

For simplicity, it is assumed that undigested manure and digestate have the same nutrient substances and availability for crops. Moeller et al. [51] demonstrated that, with some applying techniques, the soil mineral nitrogen content is not influenced by the digestion of the slurry.

Feedstock	Digestate storage	CHP	Upgrading	Upgrading technology	Name of the pathway
Maize	Open	X			I-A
Maize	Open		X	PSA	V-A (PSA)
Maize	Open		X	PWS	V-A (PWS)
Maize	Open		X	Chemical absorption	V-A (CHEM)
Maize	Open		X	Physical absorption	V-A (PHY)
Maize	Closed	X			I-B
Maize	Closed		X	PSA	V-B (PSA)
Maize	Closed		X	PWS	V-B (PWS)
Maize	Closed		X	Chemical absorption	V-B (CHEM)
Maize	Closed		X	Physical absorption	V-B (PHY)
Manure	Open	X			II-A
Manure	Open		X	PSA	VI-A (PSA)
Manure	Open		X	PWS	VI-A (PWS)
Manure	Open		X	Chemical absorption	VI-A (CHEM)
Manure	Open		X	Physical absorption	VI-A (PHY)
Manure	Closed	X			II-B
Manure	Closed		X	PSA	VI-B (PSA)
Manure	Closed		X	PWS	VI-B (PWS)
Manure	Closed		X	Chemical absorption	VI-B (CHEM)
Manure	Closed		X	Physical absorption	VI-B (PHY)
Grass	Open	X			III-A
Grass	Open		X	PSA	VII-A (PSA)
Grass	Open		X	PWS	VII-A (PWS)
Grass	Open		X	Chemical absorption	VII-A (CHEM)
Grass	Open		X	Physical absorption	VII-A (PHY)
Grass	Closed	X			III-B
Grass	Closed		X	PSA	VII-B (PSA)
Grass	Closed		X	PWS	VII-B (PWS)
Grass	Closed		X	Chemical absorption	VII-B (CHEM)
Grass	Closed		X	Physical absorption	VII-B (PHY)
Co-digestion	Open	X			IV-A
Co-digestion	Open		X	PSA	VIII-A (PSA)
Co-digestion	Open		X	PWS	VIII-A (PWS)
Co-digestion	Open		X	Chemical absorption	VIII-A (CHEM)
Co-digestion	Open		X	Physical absorption	VIII-A (PHY)
Co-digestion	Closed	X			IV-B
Co-digestion	Closed		X	PSA	VIII-B (PSA)
Co-digestion	Closed		X	PWS	VIII-B (PWS)
Co-digestion	Closed		X	Chemical absorption	VIII-B (CHEM)
Co-digestion	Closed		X	Physical absorption	VIII-B (PHY)

Table 10 – The pathways analysed in this study

4.1.2.2 Boundaries

The approach of the study is **from cradle to grave**. It means that the chain of processes covers all the phases from the cultivation (only in case of energy crops; the production of manure is not taken into account, while manure management is analysed) to the final utilisation of biogas/biomethane to produce energy. Digestate management is included in the boundaries. In Figure 15, the system boundaries of a generic pathway are represented.
Cut-off rules are not defined and considered because they are already integrated in the inventories of the processes chosen in the LCA database used.

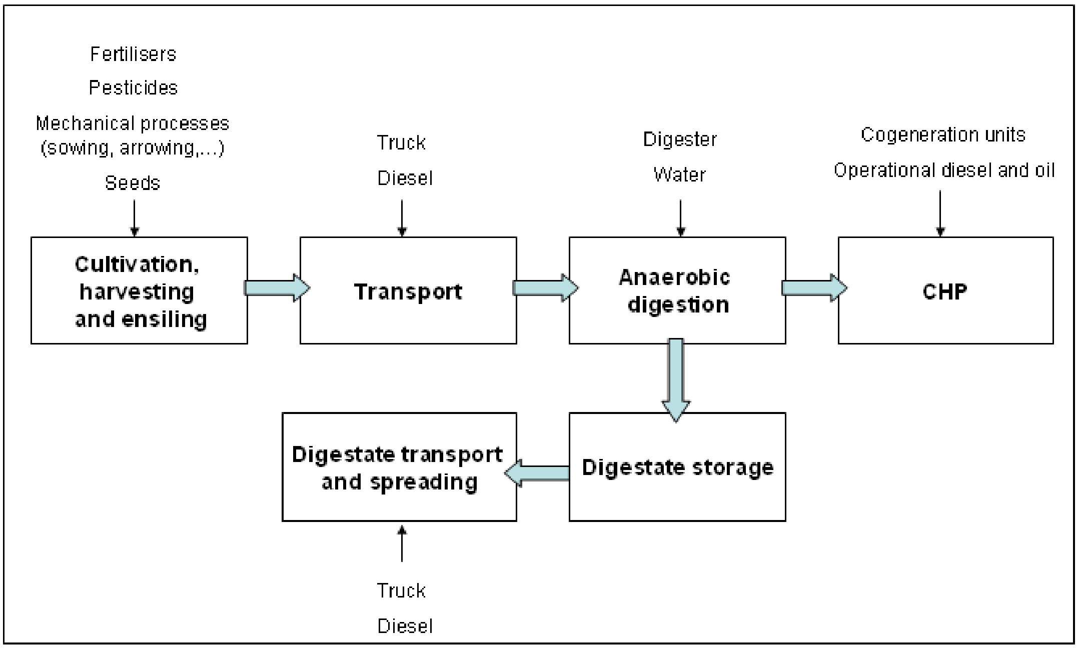


Figure 15 - System boundaries of a generic scenario of biogas production and utilisation

4.1.2.3 Multifunctionality

Except for the functional unit to which all the inputs and outputs are referred (heat for upgrading pathways or electricity for CHP pathways), biogas systems provide other products:

- the digestate to be used as fertiliser;
- heat and surplus electricity (for CHP scenarios).

The multifunctionalities are solved by system expansion:

- in case of digestion of energy crops, the amount of fertilisers that can be avoided by spreading the digestate is subtracted from the biogas system;

4.1.2.4 Impact categories and methods

Impact category	LCIA method	Unit
Climate change	CML2001 - Nov. 09, Global Warming Potential (GWP 100 years)	[kg CO_2-Equiv.]
Ozone depletion	CML2001 - Nov. 09, Ozone Layer Depletion Potential (ODP, steady state)	[kg R11-Equiv.]
Human toxicity	USETox2008, Human toxicity	[cases]
Particulate matter/Respiratory inorganics	Particulate matter inorganics	[kg PM2.5-Eq. to air]
Ionising radiation, human health	ReCiPe Midpoint (H) - Ionising radiation	[kg U_{235} eq]
Photochemical ozone formation	ReCiPe Midpoint (H) - Photochemical oxidant formation	[kg NMVOC]
Acidification	CML2001 - Nov. 09, Acidification Potential (AP)	[kg SO_2-Equiv.]
Eutrophication (freshwater)	ReCiPe Midpoint (H) - Freshwater eutrophication	[kg P eq]
Eutrophication (marine)	ReCiPe Midpoint (H) - Marine eutrophication	[kg N eq]
Ecotoxicity (freshwater)	USETox2008, Ecotoxicity	[PAF m^3.day]
Ecotoxicity (terrestrial)	ReCiPe Midpoint (H) - Terrestrial ecotoxicity	[kg 1,4-DB eq]
Resource depletion, mineral, fossil and renewable	CML2001 - Nov. 09, Abiotic Depletion (ADP elements)	[kg Sb-Equiv.]

Table 11 – Impact categories and related LCIA methods chosen for this study

The evaluation level of the impacts is midpoint. Table 11 shows the impact categories considered with the specific LCIA methods selected, if possible and available into GaBi software, between the ILCD compliant impact methods.

4.1.2.5 Data sources

Data sources for the quantification of the processes are described in each phase. Many data are taken from the database Ecoinvent 2.2.

Ecoinvent 2.2 is a database developed by the Swiss Centre for Life Cycle Inventories. It collects over 4000 datasets for products, services and processes including the areas of energy and bioenergy, transportation, waste management, construction, chemicals and agriculture, with the aim of giving a set of unified and generic LCI data of high quality. The selection of products and services to be analysed mainly relies on the market and consumption situation of the average of the European countries (RER) or of Switzerland only (CH), while references for energy are also taken from the Union for the Co-ordination of Transmission of Electricity (UCTE). The reference year is 2000, but during the course of the

updates, the period of electricity mixes and power plant performances is 2004/2005. The same year is also applied to all new datasets [24].
Ecoinvent can provide different process types. The most used are two:

- Aggregated: the inputs and the outputs are already the results of life cycle inventory of the production of the good or the service
- Unit process-single operation: the inputs are linkable to the processes of production that are responsible of the emissions.

When literature publications or updated statistics are available, this data are preferred because they can better correspond to the real scientific and technical context or be representative of the European average. However, Ecoinvent 2.2 database remains a good solution to obtain more complex datasets or information.
Also different assumptions are made when data are not available or the models are much more detailed then the requests of the goal of the study.

4.1.2.6 Deliverables

This is a comparative Life Cycle Assessment study including impact assessment and interpretation. This report represents the deliverable of the work.

4.2 LIFE CYCLE INVENTORY: DESCRIPTION OF THE PROCESSES AND DATA COLLECTION

The attributional modelling principle is chosen, since the study has to analyse the state of the art of biogas sector, without any hypothesis on policy or market changes but comparing the most common techniques regularly used in Europe.

4.2.1 Cultivation

Energy crops are cultivated with the specific purpose of obtaining biogas with digestion processes. Thus, every emission or resource consumption that occurs during the cultivation phase of the crop is taken into account.
The main inputs and outputs of the process are shown in the following tables, with the specific data sources:

INPUTS	**UNIT[4]**	**DATA SOURCE**
Fertilisers	kg	This work
Pesticides, e.g. asulam, metolachlor, glyphosate	kg	Ecoinvent 2.2
Seeding material	kg	Ecoinvent 2.2
Mechanical processes, e.g. sowing, harrowing, chopping	m^2, m^3	Ecoinvent 2.2
Transport	t·km	Ecoinvent 2.2

Table 12 – Inputs in the cultivation of energy crops

OUTPUTS	**UNIT**	**DATA SOURCE**	**COMMENT**
Crop	**kg**		**The crop has a specific yield and moisture content; output is 1 kg**
Emissions of pesticides to the soil	kg	Ecoinvent 2.2	
Heavy metals and inorganic emissions to water, soil and air	kg	Ecoinvent 2.2	Example: CO_2, N_2O, NO_x to the water and to the air, NH_3, PO_3, …

Table 13 - Outputs in the cultivation of energy crops

Each input already considers the inventory of the emissions calculated for its production. An example is given for “RER: glyphosate, at regional storehouse”: an extract of the inventory of the production of 1 kg of this pesticide is given in Figure 16. In the process of cultivation of 1

[4] In the tables with this structure, the amounts are not indicated. The amounts can be:
- not written in this report because they are not significant or they are taken from Ecoinvent 2.2 without any modification.
- written in a specific section of this report, if calculated, assumed, selected in literature or particularly interesting.

kg of silage maize, 3,25 mg of glyphosate are required: resources and emissions due to glyphosate production are then scaled.

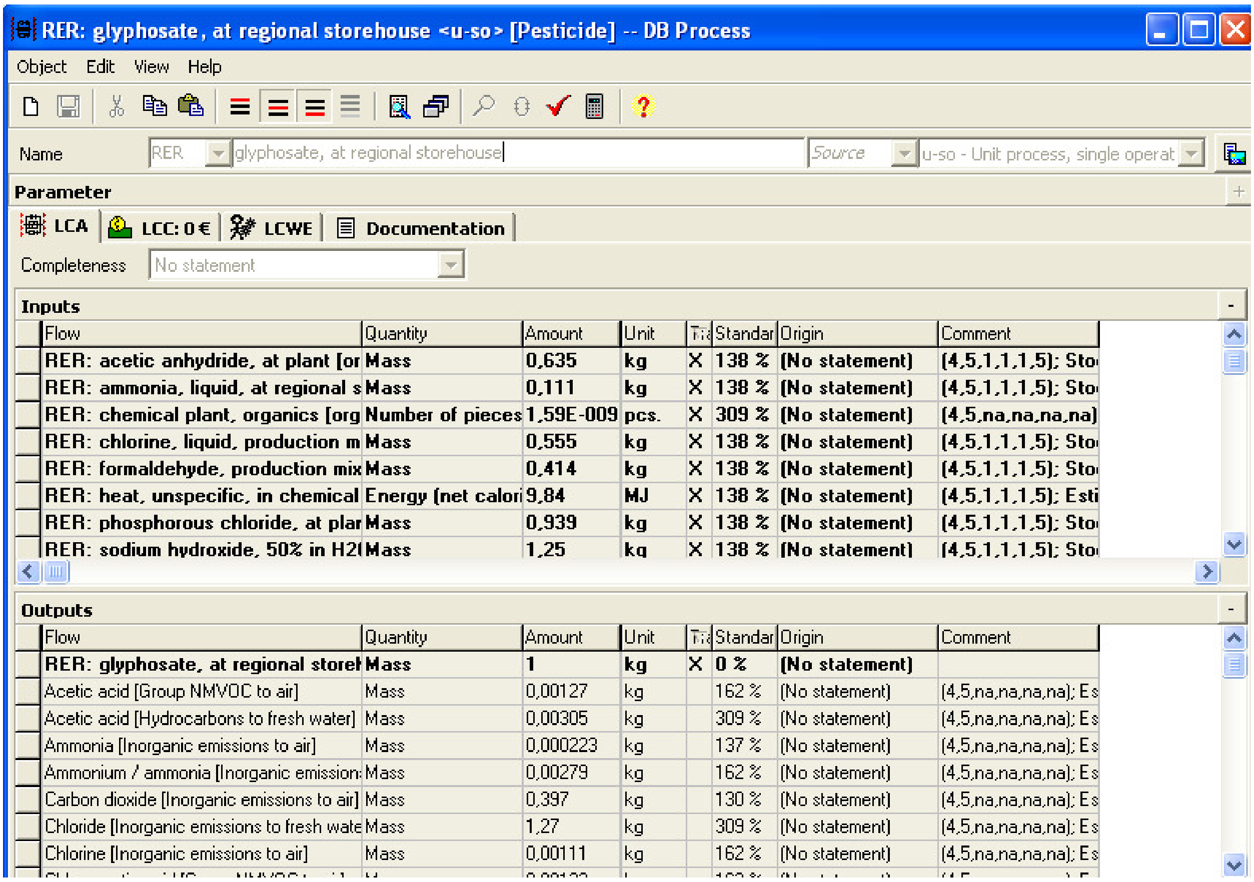


Figure 16 – Extract of Ecoinvent 2.2 model of the production of glyphosate

4.2.1.1 Fertilisers in input

The purpose of fertilisers is to ensure that the soil contains an appropriate supply of the major plant nutrients such as nitrogen (N), phosphorus (P) and potassium (K) and other secondary elements in a form that can be readily assimilated by the plant, which can then grow to its full potential. N is an essential component of plant proteins. P forms part of the nucleic acids and lipids and is essential to energy transfer. K has an important role in plant metabolism, photosynthesis, activation of enzymes and other functions. When the plant is harvested, these nutrients are harvested with it, so the soil's potential productivity decreases. The underlying principle of an effective fertilisation program is, therefore, to precisely match the nutrient inputs with the requirements of a particular plant over its growing cycle in order to maximise nutrient use efficiency, ensuring better recycling of organic waste and avoiding losses to the environment [36].

Different types of fertilisers are applied, according to Ecoinvent 2.2. Here the example for silage maize cultivation is reported.

Nitrogen fertilisers used are ammonium nitrate, ammonium sulphate, calcium ammonium nitrate, diammonium phosphate and urea. Each N-fertiliser is expressed as kg of N at field.
Phosphorus fertilisers are diammonium phosphate, phosphate rock, single and triple superphosphate and thomas meal, expressed as kg of P_2O_5 (phosphate) provided to the field.
Finally potassium fertilisers are potassium chloride and potassium sulphate, as kg of K_2O (potash) provided to the field.

In the process built, the total requirement of each nutrient and the proportion between the different kinds of fertilisers is taken form Ecoinvent 2.2 process. However, the requirement of the chemical fertilisers is reduced compared to the original data because of the employment of digestate.

4.2.2 Transport

Most of the transport is assumed to be done by a truck with a total capacity 34 - 40 t and 27 t of payload capacity, diesel driven, Euro 3.
The inventory of the process is taken from the European database for LCA ELCD [33].
The needed inputs are diesel and the feedstock that has to be transported. The data set for the diesel used describes a mass-weighted average refinery for Europe (EU-15 Diesel ELCD/PE-GaBi").
Outputs are the feedstock itself and combustion emissions (ammonia, benzene, carbon dioxide, carbon monoxide, methane, nitrogen oxides, nitrous oxide, NMVOC, particulate PM 2.5, sulphur dioxide, toluene, and xylene). NMVOC, toluene and xylene emissions of the truck result from imperfect combustion and evaporation losses via diffusion through the tank.
Truck production, end-of-life treatment of the truck and the fuel supply chain (emissions of exploration, refinery, transportation etc.) are not included in the data set [33]. These cut-offs are acceptable because in the life cycle inventory of the transport, according to ELCD with its cut-off rules, these processes are negligible.
These inputs and outputs are calculated according to some parameters (e.g. sulphur content of the fuel, percentage of different speeds within the route,…) that can be adjusted considering specific interests of the pathway. Defaults parameters are maintained in this study, except for the distance from the field to the plant.

4.2.3 Anaerobic digestion

The process of anaerobic digestion is built with GaBi Software with the following inputs and outputs, linked to the production of 1 m^3 of biogas:

INPUTS	UNIT	DATA SOURCE	COMMENT
Heat	MJ	IEA (to be published)	
Electricity	MJ	IEA (to be published)	
Feedstock	kg	This work	
Water	kg	This work	
Digester	pieces	Ecoinvent 2.2	
OUTPUTS	**UNIT**	**DATA SOURCE**	**COMMENT**
Biogas	**m^3**		**1 m^3 at 20°C**
Digestate	**kg**	**This work**	
Methane	kg	49	

Table 14 – Inputs and outputs in anaerobic digestion process

According to Liebetrau et al. [49], 0,3% of biogas produced is released in the atmosphere without being recovered (leakages). This means that the total production of biogas in the process modelled is 1,003 m^3. Therefore, all inputs are calculated in order to achieve this production. Concerning the feedstock, the water, the energy and the heat required in input, and the digestate in output, calculations are reported in each pathway.
The inventory of the production of the anaerobic digestion plant is “CH: anaerobic digestion plant, agriculture” provided by Ecoinvent 2.2.

Only methane corresponding to 0,3% of biogas lost is counted as emission in the atmosphere caused by this process.

4.2.4 Digestate storage

4.2.4.1 Open storage tank

Only the gases emitted by the digestate are accounted for, while other emissions linked such as to the construction of the tank are supposed to be included in the manufacturing of the anaerobic digestion plant. Digestate emissions can be found since digested material is never completely stabilised: it means that anaerobic reactions continue to take place. However, considering the low yield obtained, it is assumed that the loss of mass is negligible.
As said in Paragraph 4.1.1.1, emissions of N_2O, CH_4 and NH_3 are estimated. Values are taken from Amon et al. [4] and adjusted with Amon et al. [5] and scaled according to VS content of the material considered.

In Amon et al. [4], emissions from manure treated in different ways are measured and reported, both in summer and in winter temperatures. Values for anaerobically digested manure were considered. The value of the emission used here is the average between summer and winter conditions. In Amon et al. [5], the same authors divulge the slurry characteristics (total N, NH_4-N, C, DM, Ash, and pH) at the beginning and at the end of the storage of differently treated manure. These parameters are likely acceptable for fully describing the material in Amon et al. [5]. Since this material has different characteristics compared to the digestate defined in this LCA, conversions are made as explained later.

		N [g/kg]	NH_4-N [g/kg]	C [g/kg]	DM [%]	Ash [%TS]	pH
Untreated	**Start**	3,96	1,57	35,36	9,24	21,36	7,11
	End	3,25	1,82	20,05	5,74	28,58	7,80
AD	**Start**	3,17	2,13	20,38	5,57	26,48	7,65
	End	2,48	1,55	13,28	4,16	31,01	7,78

Table 15 - Slurry characteristics at the beginning and at the end of the storage of differently treated dairy cattle slurry [5]

	Emissions	CH_4 [g/m^3]	NH_3 [g/m^3]	N_2O [g/m^3]
Untreated	**Winter**	164,3	72,5	44,0
	Summer	3591,2	110,5	48,7
AD	**Winter**	111,3	62,0	40,1
	Summer	1154,2	222,5	72,4

Table 16 - Cumulated CH_4, NH_3 and N_2O emissions measured in the winter and in the summer experiment [4]

4.2.4.2 Closed storage tank

In a closed storage tank, anaerobic digestion continues to happen and the amount of biogas produced is recovered and added to the biogas obtained inside the digester. There are no significant leakages in the atmosphere, but this production of biogas affects the efficiency of the whole process since the yield of gas obtained per unit of feedstock increases.
Considering the same feedstock, the percentage of biogas recovered is equal to the one of the methane lost in case of open storage tank. The references are again Amon et al. [5] and [4].

4.2.5 Digestate transport and spreading

It is assumed that the digestate is transported to the farm by the same type of truck that carried the feedstock (see Paragraph 4.2.2). Digestate is therefore transported for the same number of km.

Concerning emissions in spreading, as said before, emissions of CH_4, N_2O and NH_3 are accounted for.

CH_4 and NH_3 are estimated with Amon et al. [5], in summer experiment (August): it is assumed that the temperature of the period in which the material is spread is comparable. The paper gives the emissions that occur during the spreading of digested and undigested manure. The same is done to evaluate the amount of N_2O emitted immediately during spreading. Concerning the second contribution of N_2O, it is assumed that the same amount of N_2O is lost when digestate or chemical fertiliser is spread: values are then already included in the process of cultivation and provided by Ecoinvent 2.2 database that follows IPCC methodology [22, 24].

Emissions	**CH_4 [g/m^3]**	**NH_3 [g/m^3]**	**N_2O [g/m^3]**
Untreated	1,3	185,8	3,8
AD	2,0	220,0	2,7

Table 17 - Emissions after field application of differently treated manure slurry [5]

The values taken from Amon et al. [5] are then scaled according to VS content of the material considered (for an example, see Paragraph 4.3.1.4). For energy crops, emissions are modified according also to nitrogen content.

4.2.6 CHP

The process in which biogas is burned to produce heat and power in cogeneration is built following an example found in Ecoinvent 2.2: “CH: biogas, agriculture covered, in cogen with ignition biogas engine”. Inputs and outputs are shown in the tables below.

According to [15], the average efficiency of recovery in a CHP device is 36% for electricity and 60% for heat. The remaining energy is lost partly as waste heat, and is partly contained in the uncombusted methane that is released because the oxidation does not have 100% efficiency. It is assumed that 1,7% of the methane contained in biogas is found in the off-gas [61, 75, 15]. It corresponds to 0,00034 $kgCH_4/MJ_{biogas}$.

The other outputs of the process are taken from Kristensen et al. [48] that measured the emission factors in different Danish CHP engines fed with biogas and provided the weighted average in function of the fuel consumed.

The quantities of the other inputs are maintained as found in Ecoinvent 2.2 database; also the life cycle inventory of their production is taken from the same database.

INPUTS	UNIT	DATA SOURCE
Biogas	m^3	Calculated
Operational diesel	kg	Ecoinvent 2.2
Mineral oil	kg	Ecoinvent 2.2
Lubricating oil	kg	Ecoinvent 2.2
Cogen. unit, common components for heat and electricity	N of pieces	Ecoinvent 2.2
Cogen. unit, components for heat only	N of pieces	Ecoinvent 2.2
Cogen. unit, components for electricity only	N of pieces	Ecoinvent 2.2

Table 18 – Inputs in biogas combustion in a CHP device

OUTPUTS	UNIT	DATA SOURCE	AMOUNT
Heat	**MJ**	**15**	0,00054000
Electricity	**MJ**	**15**	0,00032300
Carbon monoxide	kg	48	0,00032070
Methane	kg	48, 75, 15	0,00000052
Nitrogen oxides	kg	48	0,00001400
Nitrous oxide	kg	48	0,00001920
NMVOC	kg	48	0,00000263
Platinum	kg	48	0,00000000
Sulphur dioxide	kg	48	0,00000013
Formaldehyde	kg	48	0,00000021
Waste heat	MJ	15	0,00000045

Table 19 - Outputs in biogas combustion in a CHP device

4.2.7 Upgrading

The most used upgrading technologies are analysed, with the assumption that each of them causes different emissions according to various energy requirements, methane leakages and products released in the environment.
The selected technologies are Pressure swing adsorption (PSA), Water scrubbing (PWS), Chemical adsorption and Physical adsorption. When needed, also the cleaning step is accounted for.
The goal of the upgrading phase is to recover a methane-rich conditioned gas meeting these requirements assumed:

- Methane content ≥ 96% [Ecoinvent 2.2]
- $H_2S \leq 5$ mg/Nm^3 [9]

Table 20 shows a comparison between selected significant parameters for the most used upgrading techniques. In brackets, the representative values used in this LCA are visualised.

Inside the upgrading phase built in this LCA, different processes are accounted for:

- Cleaning (if required by the upgrading technology)
- Upgrading (using different technologies)
- Injection of biomethane into the grid at high pressure
- Reduction of the pressure to reach the final consumer.

While the last two steps are always done in the same way, the first two depend on the upgrading technology.

Parameter	PSA	Water scrubbing	Physical scrubbing	Chemical scrubbing
Pre-cleaning needed[5]	Yes	No	No	Yes
Working pressure [bar][6]	4-7	4-7	4-7	No pressure
Methane loss[7]	1-10% [5%]	1-2% [2%]	2-4% [3%]	<0,1% [0,1%]
Methane content	97%	98%	97%	99%
Electrical consumption [kWh/Nm^3 raw biogas][8]	0,24-0,6 [0,3]	0,2-0,6 [0,25]	0,24-0,33 [0,26]	0,11-0,15 [0,12]
Heat requirement [kWh/Nm^3 raw biogas][9]	-	-	0,16	0,44

Table 20 – Parameters of the different upgrading technologies

The Ecoinvent 2.2 process "CH: methane, 96 vol-%, from biogas, at purification" is taken as the starting point to create all the processes for each technology. It refers to a Swiss biogas upgrading plant using PSA technology. The process already considers inside these four steps [24]:

- Raw gas compression;
- H_2S removal with activated carbon: hydrogen sulphide reacts with molecular oxygen producing water and elementary sulphur that is then adsorbed on the surface of the activated carbon. Since no figures of the amount of the adsorbent required are available, it is not considered in the study. Sulphur obtained in the H_2S removal is accounted for as sulphur dioxide emission, assuming that the total amount is oxidised afterwards;
- Biogas conditioning;
- Methane separation.

The upgrading process created has the same structure reported in Table 21 and Table 22 for all the technologies analysed.

Since the calculations to obtain 1 MJ of biomethane are the same in each pathway concerning different feedstocks or storage tanks, calculations are expressed in details in the next Paragraphs.

---
[5] [57]
[6] [57]
[7] [57,63,9]
[8] [57,54,9,56]
[9] [54,9]

INPUTS	UNIT	DATA SOURCE
Biogas	**Nm^3**	
Electricity	MJ	See Table 20
Heat	MJ	See Table 20
Chemical plant	N of pieces	Ecoinvent 2.2

Table 21 – Inputs in upgrading process

OUTPUTS	UNIT	DATA SOURCE	COMMENT
Biomethane	**Nm^3**		1 Nm^3 gas composed by CH_4 for 96% in volume
Hydrogen sulphide	kg	Calculated	
Methane	kg	See Table 20	
Sulphur dioxide	kg	Calculated	
Waste heat	MJ	Calculated	

Table 22 - Outputs in upgrading process

4.2.7.1 PSA

The process found in Ecoinvent 2.2 is modified to take into account values found in literature concerning electricity consumption and methane leakages. It is assumed that the cleaning step is already performed inside this process and thus the emissions of sulphur dioxide are included.

Inputs:

Biogas = $0{,}96\frac{Nm^3CH_{4in\_UP\_gas}}{Nm^3_{UP\_gas}}\cdot\frac{1}{(1-0{,}05)}\frac{Nm^3CH_4}{Nm^3CH_{4in\_UP\_gas}}\cdot\frac{1}{0{,}55}\frac{Nm^3_{biogas}}{Nm^3CH_4}=1{,}84\,Nm^3$

Electricity =

$$0{,}3\frac{kWh}{m^3_{biogas}}\cdot 3{,}6\frac{MJ}{MWh}\cdot 1{,}84\frac{Nm^3_{biogas}}{Nm^3CH_{4in\_UP\_gas}}\cdot 0{,}96\frac{Nm^3CH_{4in\_UP\_gas}}{Nm^3_{UP\_gas}}\cdot\frac{1}{0{,}97}\frac{Nm^3_{UP\_gas}}{Nm^3CH_{4in\_UP\_gas\_eff}}\cdot$$
$$\cdot\frac{273+20}{273}\cdot\frac{m^3_{biogas}}{Nm^3_{biogas}}=2{,}11\,MJ$$

Chemical plant = Ecoinvent 2.2 = 4E-10 pieces

The emissions of the production of the chemical plant are modelled with Ecoinvent 2.2 “RER: chemical plant, organics”, while concerning electricity consumption, this will be explained in Paragraph 4.2.10.2.

Outputs:

Biomethane, 96 vol-% = 1 Nm^3

Hydrogen sulphide = Ecoinvent 2.2 = 3,49E-6 kg

$$\underline{\text{Methane}} = 0{,}55\frac{Nm^3CH_4}{Nm^3{}_{biogas}}\cdot 1{,}84Nm^3{}_{biogas}\cdot 0{,}05\frac{Nm^3CH_{4\,lost}}{Nm^3CH_4}\cdot 0{,}717\frac{Nm^3CH_4}{kgCH_4} = 0{,}0362\text{ kg}$$

Sulphur dioxide = 0,000404 kg

$$\left[\begin{array}{l}\left(0{,}00008\dfrac{Nm^3H_2S}{Nm^3{}_{biogas}}\cdot 1{,}517\dfrac{kgH_2S}{Nm^3H_2S}\cdot 1{,}84Nm^3{}_{biogas}\right)-\\(0{,}000005kgH_2S_{accepted\_out}+0{,}0000035kgH_2S_{out\_cleaning})\end{array}\right]\cdot 64\frac{kgSO_2}{mol}\cdot\frac{1}{34}\frac{mol}{kgH_2S}$$

Waste heat = Electricity

4.2.7.2 Water scrubbing

The procedures of the calculations are the same as PSA except for the hydrogen sulphide in output, obtained as follows.

$$0{,}00008\frac{Nm^3H_2S_{in}}{Nm^3{}_{biogas}}\cdot 1{,}517\frac{kgH_2S_{in}}{Nm^3H_2S_{in}}\cdot 1{,}78Nm^3{}_{biogas}-0{,}000005kgH_2S_{out}=0{,}000211\text{ kg}$$

Sulphur dioxide is supposed to be 0 because no cleaning step is required.

4.2.7.3 Physical absorption

The procedures of the calculations are the same as water scrubbing. In addition, the following amount of heat is required in input:

$$0{,}16\frac{kWh}{m^3{}_{biogas}}\cdot 3{,}6\frac{MJ}{MWh}\cdot 1{,}80\frac{Nm^3{}_{biogas}}{Nm^3CH_{4\,in\_UP\_gas}}\cdot 0{,}96\frac{Nm^3CH_{4\,in\_UP\_gas}}{Nm^3{}_{UP\_gas}}\cdot$$
$$\cdot\frac{1}{0{,}97}\frac{Nm^3{}_{UP\_gas}}{Nm^3CH_{4\,in\_UP\_gas\_eff}}\cdot\frac{273+20}{273}\cdot\frac{m^3{}_{biogas}}{Nm^3{}_{biogas}}=1{,}10\text{ MJ}$$

As a result, waste heat in output [MJ] is the sum of the MJ coming from electricity and thermal energy.

4.2.7.4 Chemical absorption

In this case, a preliminary step of cleaning is necessary, and it is modelled using Ecoinvent 2.2 “DE: sweetening, natural gas”. This process simulates the absorption of hydrogen sulphide by washing the gas with N-methyl-2-Pyrrolidone.

Inputs are adjusted making the assumption that all the natural gas needed for the process is provided by biogas. The emissions calculated in the database are maintained, except for the carbon dioxide, supposed to be biogenic and therefore considered 0.

The procedures of the calculations of the upgrading step are the same as physical absorption.

During this step, 5,7% of the energy content of the biogas is lost [24].

INPUTS	UNIT	DATA SOURCE	COMMENT
Biogas	m^3	Ecoinvent 2.2	
Chemicals	MJ	Ecoinvent 2.2	
Production plant	MJ	Ecoinvent 2.2	
Transport	tkm	Ecoinvent 2.2	
OUTPUTS	**UNIT**	**DATA SOURCE**	**COMMENT**
Biogas	$\mathbf{m^3}$		With 5 mg/Nm^3 H_2S
Emissions	**kg**	Ecoinvent 2.2	

Table 23 – Inputs and outputs in chemical absorption process

4.2.7.5 Injection into the grid

Each upgrading process is followed by a step of injection of this methane-rich gas in the grid first at high pressure, then at low pressure to reach the consumer in pipelines. The processes are taken from Ecoinvent 2.2: “CH: methane, 96 vol-%, from biogas, high pressure, at consumer”, “CH: methane, 96 vol-%, from biogas, low pressure, at consumer”. Each step implies the loss of a certain amount of the methane recovered.

In Table 24 and Table 25, inputs and outputs are represented. As usual, the LCIs of the inputs are provided by Ecoinvent 2.2 database.

INPUTS	UNIT	DATA SOURCE
Biomethane	Nm^3	Ecoinvent 2.2
Electricity	MJ	Ecoinvent 2.2
Pipeline	m	Ecoinvent 2.2
Natural gas	MJ	Ecoinvent 2.2
OUTPUTS	**UNIT**	**DATA SOURCE**
Biomethane	$\mathbf{Nm^3}$	
Carbon dioxide	kg	Ecoinvent 2.2
Hydrogen sulphide	kg	Ecoinvent 2.2
Methane	kg	Ecoinvent 2.2
Waste heat	MJ	Ecoinvent 2.2

Table 25 – Inputs and outputs in Ecoinvent 2.2: “CH: methane, 96 vol-%, from biogas, high pressure, at consumer”

INPUTS	UNIT	DATA SOURCE
Biomethane	Nm^3	Ecoinvent 2.2
Pipeline	m	Ecoinvent 2.2
Natural gas	MJ	Ecoinvent 2.2
OUTPUTS	**UNIT**	**DATA SOURCE**
Biomethane	$\mathbf{Nm^3}$	
Carbon dioxide	kg	Ecoinvent 2.2
Hydrogen sulphide	Kg	Ecoinvent 2.2
Methane	kg	Ecoinvent 2.2

Table 24 – Inputs and outputs of Ecoinvent 2.2 “CH: methane, 96 vol-%, from biogas, low pressure, at consumer”

4.2.8 Combustion of methane in boiler

The final destination of the biomethane resulting after the upgrading steps is a domestic boiler with the capacity <100kW. The combustion is modeled with a chain of Ecoinvent 2.2 processes:

- “RER: natural gas, burned in boiler atmospheric burner non-modulating <100kW”:

INPUTS	UNIT	AMOUNT
Natural gas, low pressure, at consumer	MJ	1
Gas boiler	Pieces	6,6E-7
Electricity	MJ	0,00698
OUTPUTS	**UNIT**	**AMOUNT**
Natural gas burned	**MJ**	**1**
Acetaldehyde	kg	1,0E-09
Acetic acid	kg	1,5E-07
Benzene	kg	4,0E-07
Benzo{a}pyrene	kg	1,0E-11
Butane	kg	7,0E-07
Carbon dioxide	kg	0
Carbon monoxide	kg	2,0E-06
Dust (PM2.5)	kg	1,0E-07
Formaldehyde (methanal)	kg	1,0E-06
Mercury (+II)	kg	3,0E-11
Methane	kg	2,0E-06
Nitrogen oxides	kg	1,5E-05
Nitrous oxide (laughing gas)	kg	5,0E-07
Pentane (n-pentane)	kg	1,2E-06
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD)	kg	3,0E-17
Polycyclic aromatic hydrocarbons (PAH)	kg	1,0E-08
Propane	kg	2,0E-07
Propionic acid	kg	2,0E-08
Sulphur dioxide	kg	5,5E-07
Toluene (methyl benzene)	kg	2,0E-07
Waste heat	MJ	1,11

Table 26 – Inputs and outputs of “RER: natural gas, burned in boiler atmospheric burner non-modulating <100kW”

It is assumed that the emissions in the combustion process are the same for both biomethane and natural gas. Only emissions of biogenic carbon dioxide are annulled. The inventory of the production of the gas boiler is made with Ecoinvent 2.2 data, while concerning electricity see paragraph 4.2.10.

- “RER: heat, natural gas, at boiler atmospheric non-modulating <100kW” that accepts in input 1,06 MJ of natural gas burned and gives as output 1 MJ of heat.

4.2.9 Heat

The heat necessary to warm the anaerobic reactor is provided by thermal energy produced inside the plant. It can be obtained in different ways.

4.2.9.1 CHP

In pathways considering CHP devices as final destination of the biogas, the amount of heat obtained in cogeneration with the electricity is more than the requirements of the reactor. Then it can be used, while the remaining heat is supposed to be a waste. So no additional emissions linked to the production of heat are supposed to arise.
No other requirements of heat are found in other processes inside these pathways.

4.2.9.2 Upgrading

In pathways concerning the upgrading and the injection of methane into the grid, the heat is provided by a boiler that burns a small amount of raw biogas before entering in the equipment for the removal of carbon dioxide. The Ecoinvent 2.2 processes “RER: natural gas, burned in boiler modulating <100kW” and “RER: heat, natural gas, at boiler modulating <100kW” are used, with the same kind of inputs and outputs shown in Paragraph 4.2.8. The assumption that the same gases are released when burning biogas or natural gas, except for the presence of biogenic carbon dioxide that is therefore not accounted for in biogas combustion, is taken.
The heat necessary during the upgrading process with Chemical and Physical absorption is provided by the same source.

4.2.10 Electricity

4.2.10.1 CHP

The electricity needed by the mechanical equipment of the digester is a percentage of the MJ created by the cogeneration unit. The remaining electricity is the final product of the pathway that is ready to be fed into the grid. No emissions due to electricity need are consequently accounted for.

4.2.10.2 Upgrading

Electricity demanded for running the reactor and the upgrading apparatus is taken from the grid, at low, medium or high voltage, depending on the specific requirement that are indicated in Ecoinvent 2.2 processes. The database offers the LCI of the electricity manufacturing; the geographical reference is Europe. An example is “UCTE: electricity, low voltage, production UCTE, at grid”.

4.2.11 Reference system

Considering manure as feedstock requires the introduction of the emissions caused in spreading and storing the undigested material that is not stabilised: it means that anaerobic reactions take place. Calculations will be explained in Paragraph 4.3.2.6.

4.2.11.1 CHP

The process used to compare the emissions is Ecoinvent 2.2 "RER: electricity, production mix RER". The inventory was calculated by the Swiss Centre for LCI mixing national statistics of individual countries referring to 2004.

Germany (DE) contributes to 17,4% to the total energy production, followed by France (16,5%). As an example, the energy mix of Germany is reported in Figure 17. Among the German energy mix of technologies, nuclear corresponds to 27,8%, followed by lignite and hard coal.

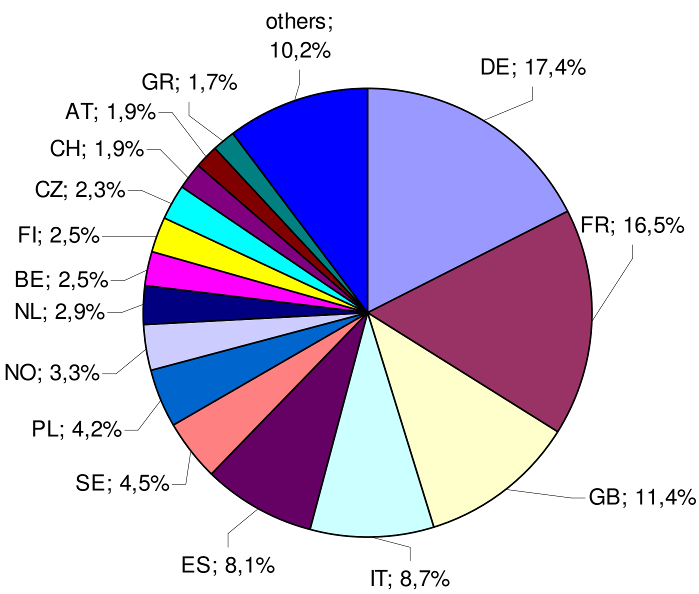


Figure 17 – European electricity production mix, Ecoinvent 2.2

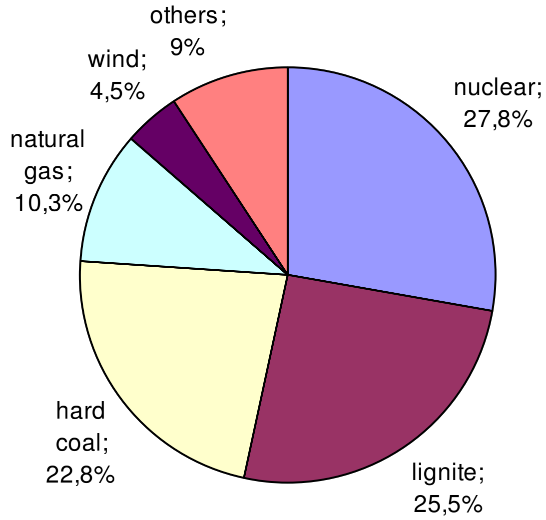


Figure 18 – German electricity production mix, Ecoinvent 2.2

4.2.11.2 Upgrading

Since the functional unit of these pathways is 1 MJ of heat, the reference system is built in order to provide this energy with the same device fed with a fossil fuel. In this case, natural gas was burnt in a boiler. The corresponding emissions are accounted for in the LCI of the process "RER: heat, natural gas, at boiler atmospheric non-modulating <100kW". The emission factors are reported in Table 26, except for the emission of 0,056 $kg/MJ_{natural\ gas\ burned}$ of fossil carbon dioxide that is accounted for.

4.3 LIFE CYCLE INVENTORY: THE PATHWAYS

4.3.1 PATHWAY I: BIOGAS FROM MAIZE, CHP

The first pathway analysed corresponds to the anaerobic digestion of maize silage that is firstly cultivated and harvested. Biogas is used in a CHP device while digestate is kept in an open storage tank (I-A) or in a closed one (I-B) and then spread at field to use its nutrient content. Figure 19 shows the main processes considered for these pathways. The functional unit is the production of 1 MJ of electricity, while the reference system accounts for the emission of the production of the same MJ of electricity from the European average mix of renewable and non-renewable resources.

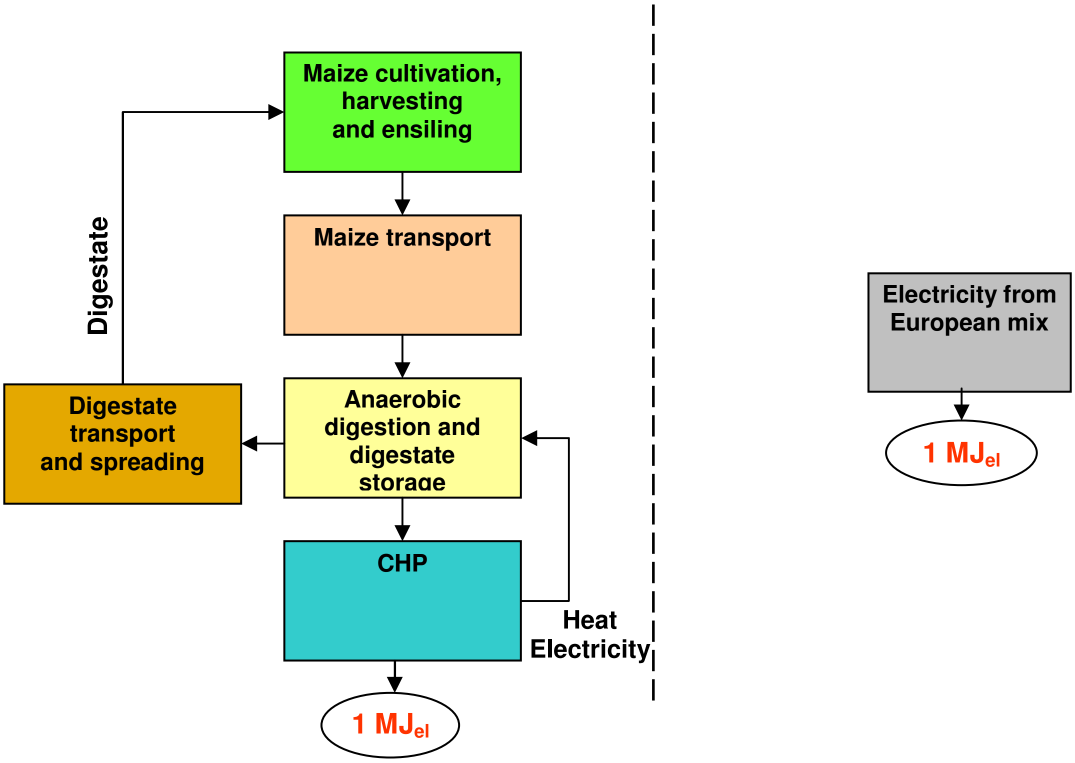


Figure 19 – Biogas from maize, CHP vs reference system

The different processes analysed, the data sources and the assumption made in the definition of the model are hereafter explained.

By mixing different sources, the following parameters shown for maize in Table 27 are assumed in this work. The feedstock SILAGE MAIZE JRC is assumed to be digested in all the pathways concerning maize.

PARAMETER	UNIT	VALUE	DATA SOURCE
Yield	$\frac{t}{ha}$	42,5	35
Moisture content	$\frac{kgH_2O}{kg}$	0,65	16, 6, 60, 65, 35
Total solids	$\frac{kgTS}{kg}$	0,35	Calculated
Volatile solids	$\frac{kgVS}{kgTS}$	0,96	16, 6
LHV	$\frac{MJ}{kgTS}$	16,7	71
LHV wet[10]	$\frac{MJ}{kg}$	5,85	Calculated
Digestate density	$\frac{kg}{m^3}$	1000	Assumption
N content	$\frac{kgN}{kg}$	0,0025	58, 50

Table 27 – MAIZE SILAGE: parameters valid for this study

4.3.1.1 Cultivation

The process SILAGE MAIZE CULTIVATION is built on the basis of the Ecoinvent 2.2 process "CH: silage maize, IP, at farm". The output is the production of 1 kg of silage maize at 72% of moisture and with the yield of 61,475 t/ha.

In Ecoinvent process, atrazine is used as a pesticide. Since it is banned in Europe (2004/248/EC, concerning the withdrawal of authorisations for plant protection products containing atrazine) it is substituted in this work with a pesticide with lower potential of damaging the human health and the environment. For that reason it is assumed that the same quantity of metolachlor is used.

The net utilisation of chemical fertiliser is calculated (and therefore assumed) to be:

- 12,67% of N fertiliser requirement
- 28,05% of P fertiliser requirement
- 0% of K fertiliser requirement

[10] The lower heating value (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25℃) and returning the temperature of the combustion products to 150℃, which assumes the latent heat of vaporization of water in the reaction products is not recovered. With this assumption, the conversion between LHV dry and LHV wet should follow this procedure:

LHV dry ·%TS - H_v·% moisture

with H_v = latent heat of vaporisation of the water at the reference temperature.

In this case, since the purpose of the utilisation of the material is not a combustion and the water does not affect the production of biogas from VS, LHV wet is calculated as:

LHW dry ·%TS.

The methodology to obtain these percentages is shown in Paragraph 4.3.1.7.

4.3.1.2 Transport

Since the process already contains the emissions linked to the harvesting and the ensiling steps, the next process analysed is MAIZE TRANSPORT from the field to the anaerobic digestion plant.

Considering a large scale plant, it is assumed an average distance from the field to the plant of 50 km [69]. The methodology utilised to define the value to introduce as distance needs to be explained.

It is clear that the different moisture content between SILAGE MAIZE JRC and the silage maize cultivated according to Ecoinvent 2.2 process means a different weight and thus different emissions in transport.

The following procedure was used to convert these two types of crops:

1 kg TS → 3,57 kg @ 72% moisture

1 kg TS → 2,86 kg @ 65% moisture

Scaling: $\frac{2{,}86}{3{,}57} = 0{,}8$

It means that the transport of 1 kg of SILAGE MAIZE JRC causes the same impacts than the transfer of 0,8 kg of silage maize as defined in Ecoinvent 2.2.

Following a more comfortable point of view, the inventory is the same if 1 kg of SILAGE MAIZE JRC is transported for 0,8 km or if 1 kg of silage maize @ 72% moisture is moved for 1 km: it is assumed to use the value of 50·0,8 = 40 km in the transport process.

4.3.1.3 Anaerobic digestion

The efficiency of the production of methane is estimated as 0,310 m^3/kgVS [15, 16, 6]. Considering the values in Table 27 and the parameters defined for biogas, the amount of 5,254 kg of silage maize is used in the process to reach the production of 1 m^3 of biogas recovered and 0,003 m^3 that result lost in the atmosphere.

In details, this is the process made to reach these results.

$$0{,}310\frac{m^3CH_4}{kgVS}\cdot\frac{1}{0{,}55}\frac{m^3{}_{biogas}}{m^3CH_4}=0{,}564\frac{m^3{}_{biogas}}{kgVS}$$

$$0{,}564\frac{m^3{}_{biogas}}{kgVS}\cdot 0{,}35\frac{kgTS}{kg}\cdot 0{,}96\frac{kgVS}{kgTS}\cdot 18{,}4\frac{MJ_{biogas}}{m^3{}_{biogas}}=3{,}48\frac{MJ_{biogas}}{kg_{maize}}$$

$$3{,}48\frac{MJ_{biogas}}{kg_{maize}}\cdot\frac{1}{5{,}85}\frac{kg_{maize}}{MJ_{maize}}=0{,}60\frac{MJ_{biogas}}{MJ_{maize}}$$

This value was calculated to consider the efficiency in terms of energy.

$$\left(0{,}60\frac{MJ_{biogas}}{MJ_{maize}}\cdot 5{,}85\frac{MJ_{maize}}{kg_{maize}}\cdot\frac{1}{18{,}4}\frac{m^3{}_{biogas}}{MJ_{biogas}}\right)^{-1}\cdot 1{,}003 = 5{,}25\frac{kg_{maize}}{m^3{}_{biogas}}$$

Since anaerobic digestion is commonly performed in the wet mode (TS content < 10%), some water needs to be added. It is necessary to add 13,13 kg water.

Digestate resulting after the digestion of silage maize has a lower mass due to the volatilisation of solids. Braun at al. [15] give the value of 0,35 $kgCH_{4produced}/kgVS_{removed}$. Considering the production of methane (in the biogas recovered and in the leakages), the reduction of VS is assumed 60%. At the average temperature of the digestion, no water evaporation occurs. Then, the digestate is 17,33 kg.

The amount of heat needed to warm the reactor is calculated starting from the value provided by JRC and calculated by mixing values of real plants (data to be published). Considering a heat requirement of 0,101 MJ/MJ_{biogas}, and assuming the LHV of biogas in Table 9, a value of 1,861 $MJ/m^3{}_{biogas}$ is added.

Electricity consumption is estimated as 0,461 $MJ/m^3{}_{biogas}$, starting from 0,025 MJ/MJ_{biogas}, with the same assumptions and references.

The supply of heat and electricity and the emissions linked are explained in Paragraph 4.2.10 and 4.2.11.

4.3.1.4 Digestate storage in open tank (I-A)

Firstly, it is necessary to convert the emission found in literature according to the VS content of the mixture of maize and water; the example shows the case of CH_4 found in the winter experiment. Data found in Amon et al. [5, 4] are reported in Table 15 and Table 16, while values taken as representative for this study are contained in Table 18.

$$0{,}10\frac{kgTS}{kg_{mixture}}\cdot 0{,}96\frac{kgVS}{kgTS}\cdot(1-0{,}6)\frac{kgVS_{digestateJRC}}{kgVS} = 0{,}0384\frac{kgVS_{digestateJRC}}{kg_{mixture}}$$

$$111{,}3\frac{gCH_4}{m^3{}_{digestate}}\cdot\frac{1}{0{,}0557}\frac{kg}{kgTS}\cdot\frac{1}{(1-0{,}2648)}\frac{kgTS}{kgVS}\cdot 0{,}0384\frac{kgVS_{JRC}}{kg_{JRC}}\cdot\frac{18{,}38}{17{,}33}\frac{kg_{mixture}}{kg_{digestate}} = 110{,}2\frac{gCH_4}{m^3{}_{digestate}}$$

Then, the average of summer and winter emissions is supposed to be the most representative. As in summer 1076,7 $gCH_4/m^3{}_{digestate}$ are obtained, the average results 593,3 $gCH_4/m^3{}_{digestate}$ that corresponds to 0,0005933 $kgCH_4/kg_{digestate}$.

Concerning N_2O, another conversion is necessary in order to respect the lower N content in maize [58]. With the same procedure and references, the average emission results 0,0000527 $kgN_2O/kg_{digestate}$.

$$0{,}0000527\,\frac{kgN_2O}{kg_{digestate}}\cdot 0{,}008929\,\frac{kgN_{maize}}{kgTS}\cdot\frac{1}{0{,}05691}\,\frac{kgTS}{kgN_{manure}}=0{,}0000083\,\frac{kgN_2O}{kg_{digestate}}$$

The same procedure is done to estimate NH_3. The result is 0,0000209 $kgNH_3/kg_{digestate}$.

4.3.1.5 Digestate storage in closed tank (I-B)

Keeping the storage tank closed and recovering the gas produced during anaerobic process that bacteria continue to do, allow to have an additional amount of biogas estimated in 0,00162 $m^3/kg_{digestate}$. This amount was obtained considering that the production of gases described in Paragraph 4.3.1.4 is the same: it means that the methane represents the 55% of the total biogas recovered in this section. No other leakages are supposed to be found because of the recovery of all the gases produced.

4.3.1.6 Digestate transport and spreading at field

Digestate is transported for 50 km.

The process of the spreading accounts for only the emissions of N_2O, CH_4 and NH_3 from the material because the process of putting the digestate on the field with machinery is supposed to be already accounted for in the cultivation phase. It is therefore assumed that digestate is distributed in the same way (with the same devices, and thus with the same emissions and fuel consumption) as a chemical fertiliser.
The reference is Amon et al. [5] (see Paragraphs 4.2.4.1 and 4.2.5 for the values). The calculation represents the emissions of methane:

$$2\,\frac{gCH_4}{m^3{}_{digestate}}\cdot\frac{1}{0{,}0416}\,\frac{kg}{kgTS}\cdot\frac{1}{(1-0{,}3101)}\,\frac{kgTS}{kgVS}\cdot 0{,}0384\,\frac{kgVS}{kg}\cdot\frac{18{,}38}{17{,}33}\,\frac{kg_{mixture}}{kg_{digestate}}=2{,}8\,\frac{gCH_4}{m^3{}_{digestate}}$$

As shown for the storage tank, emissions of nitrogen compounds should be corrected according to nitrogen content in digestate.

Table 28 summarise all the emissions linked to digestate management.

Emissions	Storing (open air)	Storing (closed tank)	Spreading	Unit
CH_4	0,0005933	0	0,0000004	$\frac{kgCH_4}{kg_{digestate}}$
N_2O	0,0000083	0	0,0000006	$\frac{kgN_2O}{kg_{digestate}}$
NH_3	0,0000209	0	0,0000462	$\frac{kgNH_3}{kg_{digestate}}$

Table 28 – Methane, nitrous oxide and ammonia emitted from maize digestate

4.3.1.7 Production of organic fertiliser from digestate

Spreading digestate in agricultural fields allows lowering the requirement of chemical fertilisers providing N, P and K to the plants. This corresponds to a significant reduction of the emissions linked to the production of the fertilisers.

It should be notice that spreading chemical fertilisers releases substances because of leaching, volatilisation, emissions. Ecoinvent 2.2 considers all these emissions in the process of cultivation of maize. At this stage, the values found in Ecoinvent 2.2 are not modified; this could lead to over-estimate the emissions when chemical fertilisers are replaced by digestate.

Some studies quantify that the total of nutrients contained in the digestate that are available for the plant can replace 100% of chemical P and K, while 30-40% of N fertiliser is still required [13, 1].

However, calculations are made to understand the effective balance of the nutrients in the life cycle of the treatment of the cultivation.

- **Phosphorus (P)**

Maize requires the amount of phosphorus-based fertilisers shown in Table 29.

Fertiliser required	kgP_2O_5/kg	% of the total P
single superphosphate	1,85E-05	1,66%
thomas meal	5,79E-05	5,20%
triple superphosphate,	0,00045815	41,10%
Diammonium phosphate	0,00031202	27,99%
phosphate rock	0,00026813	24,05%

Table 29 – P fertiliser required in maize silage cultivation

The average of [58] and [50] is taken as representative of the P contained in the plant, as 0,00035 kgP/kg. Considering no significant losses of phosphorus during anaerobic digestion and the all chain of processes, it is assumed that the same quantity of P is contained in digestate. It is also assumed that all the phosphorus in the digestate that is used as fertiliser is ready to be absorbed by the plants during their growing phases. Therefore, the amount of chemical fertiliser required is calculated as the difference between the amount of P needed by the plant and the P contained in digestate.

Since the fertilisers are expressed as kg of P_2O_5, the conversion to or from P is made with stoichiometric adaptations.

As a result, 71,95% of the chemical fertilisers that should be spread in order to assure the P necessary to the plant to grow can be avoided by recycling the nutrients that the plant took, while the remaining 28,05% is still to be provided by chemical additions. This amount is divided into the different fertilisers considering the percentages shown in Table 29.

- **Potassium**

Only potassium chloride and potassium sulphate are used, corresponding to 0,0017464 kgK_2O/kg (93,84%) and 0,0001146 kgK_2O/kg (6,16%).

K contained in maize is assumed as 0,0035 kgK/kg (average of [58] and [50]).

With the same assumption and the same method expressed for P, no remaining chemical need results. Instead, an additional production of 26,65% of K-fertiliser is obtained. This could mean that the plant intakes potassium from the soil; while returning the digestate into the agricultural soil, nutrients recirculation is allowed. Therefore, the K requirement in the cultivation of maize is equal to zero, with no emission coming from the production of potassium fertilisers.

In addition, the production of an extra quantity of 26,65% of the mix of the potassium fertilisers is avoided, and consequently the emissions related. In other terms, producing 1 MJ of electricity can provide an extra content of K_2O necessary to cultivate about 5,5 m^2 of soil with maize and therefore the emissions for producing this quantity are avoided.

- **Nitrogen**

Maize requires the amount of nutrients shown in Table 30. N contained in maize is assumed as 0,0025 kgN/kg (average of [58] and [50]), 11,25% of which is NH_4-N [50].

Fertiliser required	kgN/kg	% of the total N
ammonium nitrate	0,00040725	44,88%
ammonium sulphate	0,00003080	3,40%
calcium ammonium nitrate	0,00020425	22,51%
Urea	0,00014302	15,76%
diammonium phosphate	0,00012209	13,45%

Table 30 - N fertiliser required in maize silage cultivation

In this case, the loss of N compounds are not negligible: since ammonia and nitrous oxide emissions occurs during spreading, it is necessary to subtract this contribution to the total nitrogen that can be found in the digestate considering the content of a maize whole plant. Also the leakages due to the storage in open air should be considered; it is assumed finally that even if the tank is closed, the same amount of N is lost in the biogas.

A further hypothesis is made: only NH_4-N is immediately available for the plants [50]. According to Weiland [73], during anaerobic digestion mineral nitrogen increases of a factor of 3, while total nitrogen remains approximately the same.

Thus, this is the procedure followed to reach the result:

N-Fertiliser required**:** Sum of ammonium nitrate; ammonium sulphate; calcium ammonium nitrate; urea; diammonium phosphate

N content in Maize: Average of ECN [58] and IEA values [50]

N content in digestate: N content in maize – (sum of N emissions as ammonia and N_2O)

N available in digestate: NH_4-N digestate = N content in digestate * %N-NH_3 of total N in feedstock * 3

N-Fertiliser required after digestate application: N-Fertiliser required – N available in digestate = 12,67 % of N-Fertiliser required.

	Without digestate [Ecoinvent 2.2]	With digestate	Unit
potassium chloride	0,0017464	-0,0004653	kgK_2O/kg
potassium sulphate	0,00011455	-3,05E-05	kgK_2O/kg
single superphosphate	1,85E-05	5,18E-06	kgP_2O_5/kg
thomas meal	5,79E-05	1,62E-05	kgP_2O_5/kg
triple superphosphate,	0,00045815	1,28E-04	kgP_2O_5/kg
diammonium phosphate	0,00031202	8,75E-05	kgP_2O_5/kg
phosphate rock	0,00026813	7,52E-05	kgP_2O_5/kg
ammonium nitrate	0,00040725	5,16E-05	kgN/kg
ammonium sulphate	3,08E-05	3,90E-06	kgN/kg
calcium ammonium nitrate	0,00020425	2,59E-05	kgN/kg
urea	0,00014302	1,81E-05	kgN/kg
diammonium phosphate	0,00012209	1,55E-05	kgN/kg

Table 31 – Chemical fertilisers in input in the process of cultivation, without and with the utilisation of digestate

4.3.1.8 Results with GaBi software

The following picture represents the flow diagrams of the processes considered and explained. Fixing the functional unit of 1 MJ of electricity, the software automatically refers all the inputs and the outputs to this value. The arrows show the flux of materials or energy (reference quantity) that pass through the processes. In green, the feedstock goes from the cultivation to the digester thanks to a transportation process. Digestate (in brown) links the digestion with the spreading. Biogas (in blue) is burnt in a CHP device once it is produced. Electricity (yellow), that is produced by the CHP apparatus, is partly used inside the digester while the rest is fed into the grid. Finally, heat (in red) is used to warm the reactor while the remaining amount is released in the atmosphere.

The two pathways seem analogous because the only difference concerns the recovery of biogas from the storage tank that in these flowgrams is not depicted but occurs inside the digestion box. As a result, the software calculates that to produce the same functional unit less biomass is required when the storage tank is closed. This increases the efficiency of the all process, saving an amount of maize of around 40 g for MJ_{el} produced.

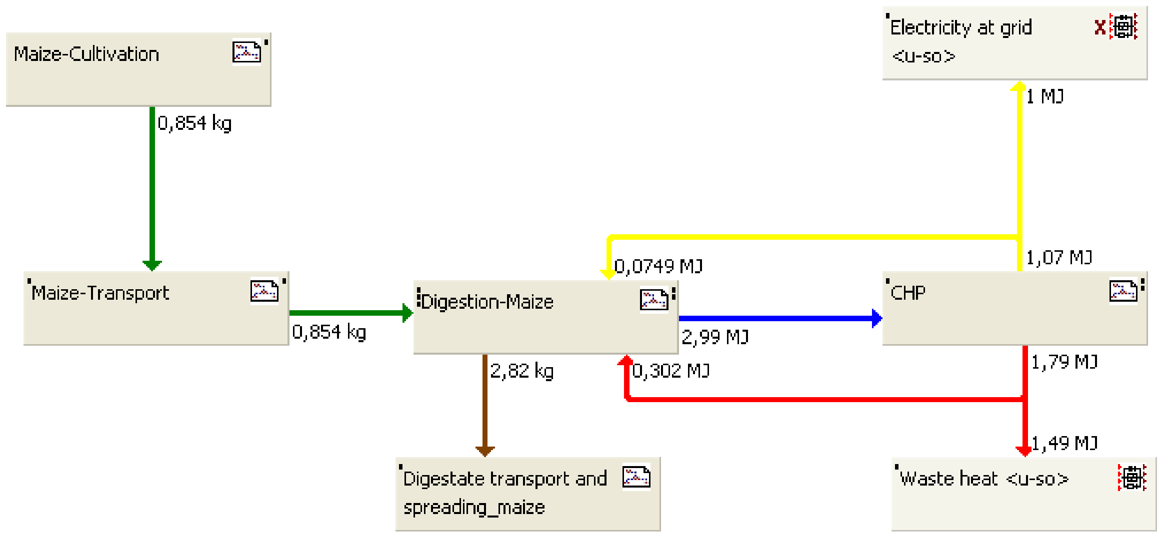


Figure 20 - Pathway I-A[11]

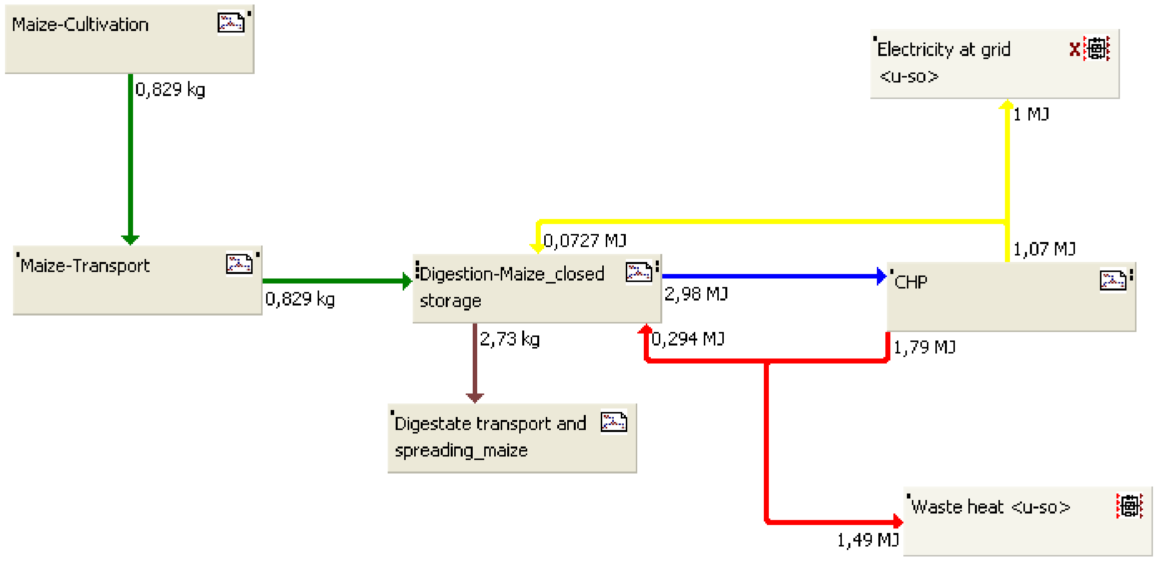


Figure 21 - Pathway I-B

[11] The arrows (and the relative quantities) represents the following flows: Green: maize silage, Brown: digestate, Blue: biogas, Red: thermal energy, Yellow: electricity

4.3.2 PATHWAY II: BIOGAS FROM MANURE, CHP

The second pathway represents the anaerobic digestion of animal manure. Biogas is used in a CHP device while digestate is kept in an open storage tank (II-A) or in a closed one (II-B) and then spread at field to use its nutrient content. The functional unit is 1 MJ of electricity, while the reference system accounts for both the emission of the production of 1 MJ_{el}, as seen in the previous Pathway I, and the ones due to storage and spreading of the same amount of untreated manure.

Figure 22 shows the main processes considered for this pathway.

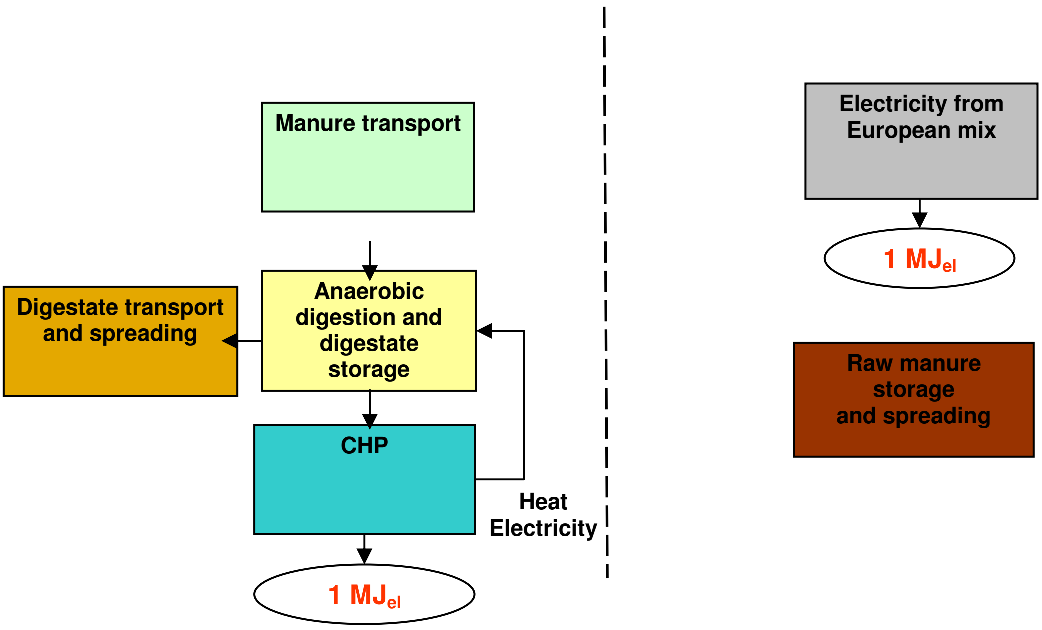


Figure 22 – Biogas from manure vs reference system without credits

The feedstock MANURE JRC is defined with the parameters shown in Table 32.

PARAMETER	UNIT	VALUE	DATA SOURCE
Moisture content	$\frac{kgH_2O}{kg}$	0,85	26
Total solids	$\frac{kgTS}{kg}$	0,15	Calculated
Volatile solids	$\frac{kgVS}{kgTS}$	0,80	26
LHV	$\frac{MJ}{kgTS}$	12	64
LHV wet	$\frac{MJ}{kg}$	1,8	Calculated
Digestate density	$\frac{kg}{m^3}$	1000	Assumption

Table 32 – MANURE JRC: parameters valid for this study

4.3.2.1 Transport

Considering a large scale plant, it is assumed an average distance from the field to the plant of 10 km [69].

4.3.2.2 Anaerobic digestion

The efficiency of the production of methane is estimated as 0,165 m^3/kgVS [average of 6, 26, 46, 3], corresponding to 25,667 kg of manure necessary to produce 1 m^3 of biogas recovered and 0,003 m^3 that result lost in the atmosphere.

In details:

$$0{,}165\,\frac{m^3CH_4}{kgVS}\cdot\frac{1}{0{,}55}\,\frac{m^3{}_{biogas}}{m^3CH_4}=0{,}300\,\frac{m^3{}_{biogas}}{kgVS}$$

$$0{,}300\,\frac{m^3{}_{biogas}}{kgVS}\cdot 0{,}15\,\frac{kgTS}{kg}\cdot 0{,}80\,\frac{kgVS}{kgTS}\cdot 18{,}4\,\frac{MJ_{biogas}}{m^3{}_{biogas}}=0{,}66\,\frac{MJ_{biogas}}{kg_{manure}}$$

$$0{,}66\,\frac{MJ_{biogas}}{kg_{manure}}\cdot\frac{1}{1{,}80}\,\frac{kg_{manure}}{MJ_{manure}}=0{,}37\,\frac{MJ_{biogas}}{MJ_{manure}}$$

This value was calculated to consider the efficiency in terms of energy.

$$\left(0{,}37\,\frac{MJ_{biogas}}{MJ_{manure}}\cdot 1{,}80\,\frac{MJ_{manure}}{kg_{manure}}\cdot\frac{1}{18{,}4}\,\frac{m^3{}_{biogas}}{MJ_{biogas}}\right)^{-1}\cdot 1{,}003=25{,}67\,\frac{kg_{manure}}{m^3{}_{biogas}}$$

It is assumed that with 15% TS no additional water is strictly necessary. In addition, the reduction of VS during digestion is assumed equal to 45% [26, 46], but it is supposed that the feedstock does not change in weight during anaerobic digestion, because of its low yield. Thus, digestate is 25,67 kg.

It is considered that the digester for both maize and manure require the same thermal energy in input, calculated as 1,861 MJ/m^3_{biogas}

Electricity consumption is estimated as 0,369 MJ/m^3 biogas, starting from 0,02 MJ/MJ_{biogas} (data to be published), assuming the LHV of biogas in Table 9.

The supply of heat and electricity and the emissions linked are explained in Paragraph 4.2.10 and 4.2.11.

4.3.2.3 Digestate storage in open tank (II-A)

As seen in Paragraph 4.3.1.4, it is necessary to convert the emission found in literature according to the VS content of MANURE JRC; the example shows the case of CH_4 found in the winter experiment. Data found in Amon et al. [5, 4] are reported in Table 6 and 7, while values taken as representative for this study are contained in Table 20.

$$0{,}15\,\frac{kgTS_{manure}}{kg_{manure}}\cdot 0{,}80\,\frac{kgVS_{manure}}{kgTS_{manure}}\cdot(1-0{,}45)\,\frac{kgVS_{digestateJRC}}{kgVS_{manure}}=0{,}066\,\frac{kgVS_{digestateJRC}}{kg_{manure}}$$

$$111{,}3\,\frac{gCH_4}{m^3{}_{digestate}}\cdot\frac{1}{0{,}0557}\frac{kg}{kgTS}\cdot\frac{1}{(1-0{,}2648)}\frac{kgTS}{kgVS}\cdot 0{,}066\,\frac{kgVS_{JRC}}{kg_{JRC}}=179{,}4\,\frac{gCH_4}{m^3{}_{digestate}}$$

Then, the average of summer and winter emissions is supposed to be the most representative. As in summer 1860,2 $gCH_4/m^3{}_{digestate}$ are obtained, the average results 1019,8 $gCH_4/m^3{}_{digestate}$ that corresponds to 0,001020 $kgCH_4/kg_{digestate}$.

Concerning N_2O and NH_3, no conversion about nitrogen is made because it is supposed that MANURE JRC contains the same amount of N as the feedstock of the experiment [5, 4]

4.3.2.4 Digestate storage in closed tank (II-B)

Keeping the storage tank closed and recovering the gas produced allows having an additional amount of biogas estimated in 0,001948 $m^3/kg_{digestate}$. No other leakages are accounted for.

4.3.2.5 Digestate transport and spreading at field

Digestate is transported for 10 km with a truck (see Paragraph 4.2.2). In addition, in this case the emissions caused by the spreading equipment should be considered. The process "CH: slurry spreading, by vacuum tanker" gives as output the emissions caused by the mechanical work of distribution of a cubic meter of slurry, while it considers as input diesel and machinery.

The process of the spreading accounts for the emissions of N_2O, CH_4 and NH_3 as found in Amon et al. [5] (see Paragraph 4.2.4.1 and 4.2.5 for the values). The calculation represents the emissions of methane:

$$2\,\frac{gCH_4}{m^3{}_{digestate}}\cdot\frac{1}{0{,}0416}\frac{kg}{kgTS}\cdot\frac{1}{(1-0{,}3101)}\frac{kgTS}{kgVS}\cdot 0{,}066\,\frac{kgVS}{kg}=4{,}6\,\frac{gCH_4}{m^3{}_{digestate}}=0{,}0000046\,\frac{kgCH_4}{kg_{digestate}}$$

In Table 33, all the emissions of digestate management are collected.

Emissions	Storing (open air)	Storing (closed tank)	Spreading	Unit
CH_4	0,0010198	0	0,0000046	$\frac{kgCH_4}{kg_{digestate}}$
N_2O	0,0000906	0	0,0000062	$\frac{kgN_2O}{kg_{digestate}}$
NH_3	0,0002293	0	0,0005059	$\frac{kgNH_3}{kg_{digestate}}$

Table 33 - Methane, nitrous oxide and ammonia emitted from manure digestate

4.3.2.6 Reference system and credits

As said in Paragraph 4.2.11, the reference system corresponds to the production of 1 MJ of electricity as an European mix, but the alternative fate of undigested manure has to be analysed. It is supposed that the agricultural practice consists in recycling the nutrient content of the animal slurry distributing it as a fertiliser on cultivated soil. It is supposed that raw manure provides the same quantity of nutrients as digested manure, but the emissions that occur during the storage period (in an open tank) and the spreading phase are different. The reference system should definitely account for the emissions due to undigested manure.

As seen for digestate emissions occurring in storing, N_2O, CH_4 and NH_3 are estimated with the same assumption (average and with values taken from Amon et al. [5] and adjusted with Amon et al. [4]) scaled according to VS content of the material considered. These are the results of the winter experiment concerning methane:

$$0{,}15\,\frac{kgTS_{manure}}{kg_{manure}}\cdot 0{,}80\,\frac{kgVS_{manure}}{kgTS_{manure}} = 0{,}12\,\frac{kgVS_{manure}}{kg_{manure}}$$

$$164{,}3\,\frac{gCH_4}{m^3{}_{manure}}\cdot\frac{1}{0{,}0924}\,\frac{kg}{kgTS}\cdot\frac{1}{(1-0{,}2136)}\,\frac{kgTS}{kgVS}\cdot 0{,}12\,\frac{kgVS}{kg} = 271{,}3\,\frac{gCH_4}{m^3{}_{manure}}$$

The average of summer and winter conditions gives the value of 0,003101 $kgCH_4/kg_{digestate}$.

As far as spreading emissions is concerned, the same calculations made for digested manure are proposed:

$$1{,}3\,\frac{gCH_4}{m^3{}_{manure}}\cdot\frac{1}{0{,}0574}\,\frac{kg}{kgTS}\cdot\frac{1}{(1-0{,}2858)}\,\frac{kgTS}{kgVS}\cdot 0{,}12\,\frac{kgVS}{kg} = 3{,}8\,\frac{gCH_4}{m^3{}_{manure}} = 0{,}0000038\,\frac{kgCH_4}{kg_{manure}}$$

Again, the work of the agricultural instruments has to be considered.

In Table 34, the gases emitted by the raw manure stored and distributed are reported:

Emissions	Storing	Spreading	Unit
CH_4	0,0031010	0,0000038	$\frac{kgCH_4}{kg_{manure}}$
N_2O	0,0000765	0,0000111	$\frac{kgN_2O}{kg_{manure}}$
NH_3	0,0001511	0,0005439	$\frac{kgNH_3}{kg_{manure}}$

Table 34 - Methane, nitrous oxide and ammonia emitted from undigested manure

A different approach consists in taking into account only energy production in the reference system and considering the emissions of undigested manure as avoided in biogas system (referred as *credits*). In practice, this means:

- subtracting the emissions shown in Table 34 in biogas system. It is done by creating a process in which these amounts of gases are included in input;
- neglecting the process of transport and spreading of both manure and digestate because it is supposed to be done in the same way, thus the same emissions would be found in input and in output, giving zero as a result.

The final results in terms of GHG savings are the same. However, using credits approach is useful when a comparison between manure and other feedstocks providing the same functional unit is required.

4.3.2.7 Results with GaBi software

As an example, Pathway II-B is visualised. The main consideration is that because of the low biogas yield more biomass in input is required.

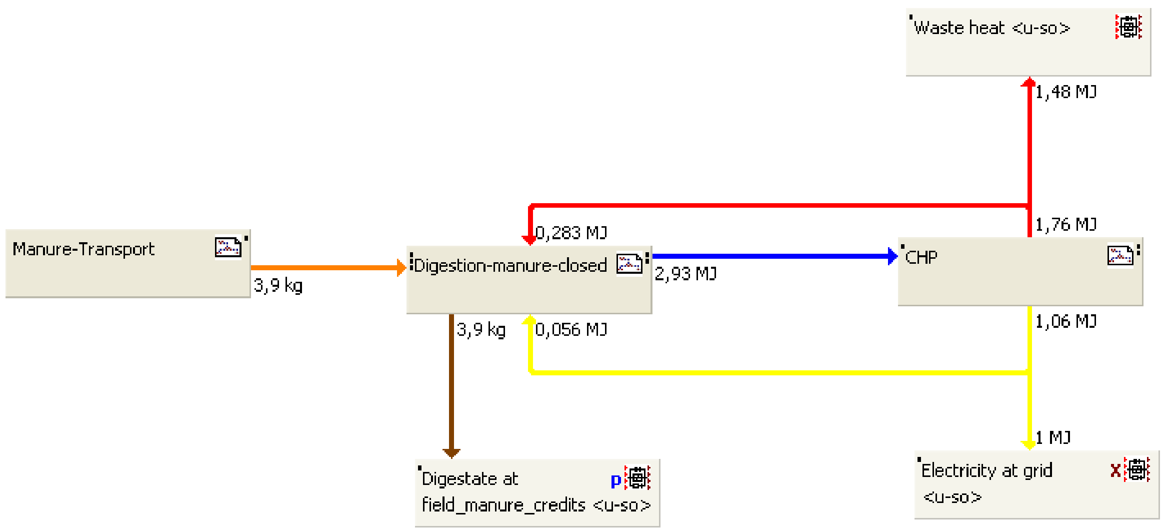


Figure 23 – Pathway II-B[12]

[12] The arrows (and the relative quantities) represent the following flows: Orange: MANURE JRC, Brown: digestate, Blue: biogas, Red: thermal energy, Yellow: electricity

4.3.3 PATHWAY III: BIOGAS FROM GRASS, CHP

In this pathway, grass is the feedstock cultivated, harvested and fed to the digester in form of silage. The subsequent processes are those already explained for maize, and the same functional unit and reference system are considered. As usual, both open (III-A) and closed (III-B) storage of the digestate are considered.

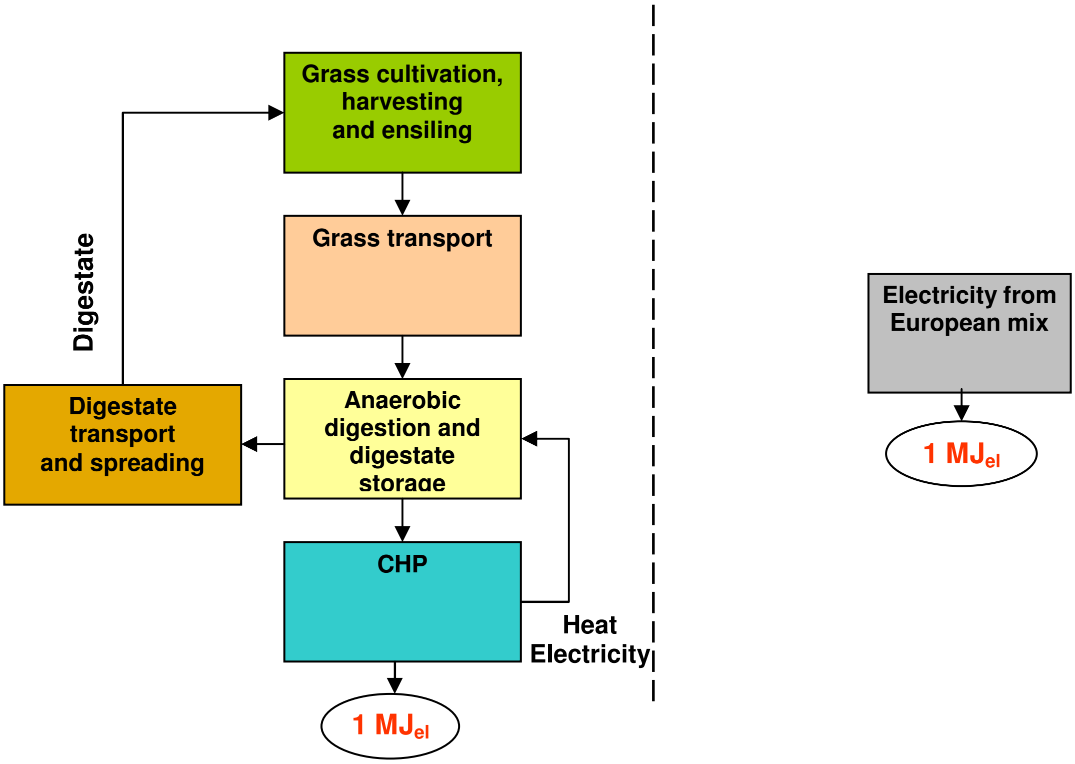


Figure 24 – Biogas from grass silage vs reference system

The following parameters are assumed in order to consider the average of the characteristics found in literature for European grass used in biogas production:

4.3.3.1 Cultivation

The process used is Ecoinvent 2.2 "CH: grass silage IP, at farm". The output is the production of 1 kg of dry matter of grass silage.

Grass requires only nitrogen fertilising: Ecoinvent 2.2 assumes that only ammonium nitrate is applied (0,00247 kgN/kg_{grass})

The net utilisation of ammonium nitrate is calculated (and therefore assumed) to be 0,002206 kgN/kg_{grass}, the 89,33% of the amount required according to Ecoinvent 2.2.

The methodology used to calculate this value is shown in Paragraph 4.3.3.5.

PARAMETER	UNIT	VALUE	DATA SOURCE
Yield	$\frac{t}{ha}$	29,1	Calculated
Yield of TS	$\frac{kgTS}{ha}$	10,2	13, 15, 25, 38, 0
Moisture content	$\frac{kgH_2O}{kg}$	0,65	15
Total solids	$\frac{kgTS}{kg}$	0,35	Calculated
Volatile solids	$\frac{kgVS}{kgTS}$	0,92	53
LHV	$\frac{MJ}{kgTS}$	18,8	53
LHV wet	$\frac{MJ}{kg}$	6,58	Calculated
Digestate density	$\frac{kg}{m^3}$	1000	Assumption
N content	$\frac{kgN}{kg}$	0,0072	66, 50

Table 35 – GRASS SILAGE: parameters valid for this study

4.3.3.2 Transport

In the transport process it is important to account for the total weight of grass silage by including also the moisture. It is assumed that silage grass has 65% moisture [15]. The conversion consists in taking into account that for 1 kgTS, 2,86 kg of grass silage are transported by truck.

Considering a large scale plant, it is assumed an average distance from the field to the plant of 50 km [69]. The means of transport is the same truck as mentioned in Paragraph 4.3.2.

4.3.3.3 Anaerobic digestion

The yield of methane production is estimated to be 0,348 m^3CH_4/kgVS [15, 38, 53, 52]. Considering the values indicated in Table 35 and the parameters defined for biogas, the amount of 4,518 kg of silage grass are used in the process to reach the production of 1 m^3 of biogas recovered and 0,003 m^3 lost in the atmosphere, due to leakages. The process made to obtain these results is shown Paragraph 4.3.2.2. because it is the same as maize.

Water required to guarantee 10% of TS in the digester is 12,28 kg. Digestate resulting after the digestion of silage grass has a lower mass due to the volatilisation of solids. Braun at al. [15] give the value of 0,35 $kgCH_{4produced}/kgVS_{removed}$. Considering the production of methane (in the biogas recovered and in the leakages), the reduction of VS is assumed 60%. At the average temperature of the digestion, no water evaporation occurs. Then, the digestate is 16,24 kg.

Electricity and heat consumptions are supposed to be the same required for maize.

4.3.3.4 Digestate storage in open tank (I-A) or closed tank (I-B), transport and spreading

Since the calculations performed are the ones already expressed referring to maize pathways (see Paragraph 4.3.1.4), in the following table only the results of the calculations are added. The nitrogen content of the grass is assumed to be 0,0071 kgN/kg (average of [66] and [50]).

Emissions	Storing (open air)	Storing (closed tank)	Spreading	Unit
CH_4	0,0005933	0	0,0000010	$\frac{kgCH_4}{kg_{digestate}}$
N_2O	0,0000190	0	0,0000013	$\frac{kgN_2O}{kg_{digestate}}$
NH_3	0,0000482	0	0,0001063	$\frac{kgNH_3}{kg_{digestate}}$

Table 36 - Methane, nitrous oxide and ammonia emitted from grass digestate

Keeping the storage tank closed and recovering the gas produced allow to have an additional amount of biogas estimated in 0,001615 $m^3/kg_{digestate}$.

Digestate is then transported for 50 km (it is assumed that grass and maize have the same logistics).

4.3.3.5 Production of organic fertiliser from digestate

Since no study was found in literature specifying the specific composition of digestate produced from the digestion of grass, it is assumed that the considerations made for maize silage in Paragraph 4.3.1.7 are valid also for this feedstock. However, different plant composition, nutrients requirement and leakages mean that the results in terms of avoided chemical fertilisers are not the same.

It is assumed that 1,29% the total nitrogen contained in grass silage is in the form of NH_4-N [66]. Considering this as the amount of nitrogen immediately available for the plants [50] and assuming the increase of mineral nitrogen of a factor of 3 during anaerobic digestion [73], the result is the following.

N-Fertiliser required: 0,00247 kgN/kg

N content in grass: 0,0071 kgN/kg

N content in digestate: N content in grass – (sum of N emissions as ammonia and N_2O)

N available in digestate: NH4-N digestate = N content in digestate * 1,29% * 3

N-Fertiliser required after digestate application: 90,18%

4.3.3.6 Results with GaBi software

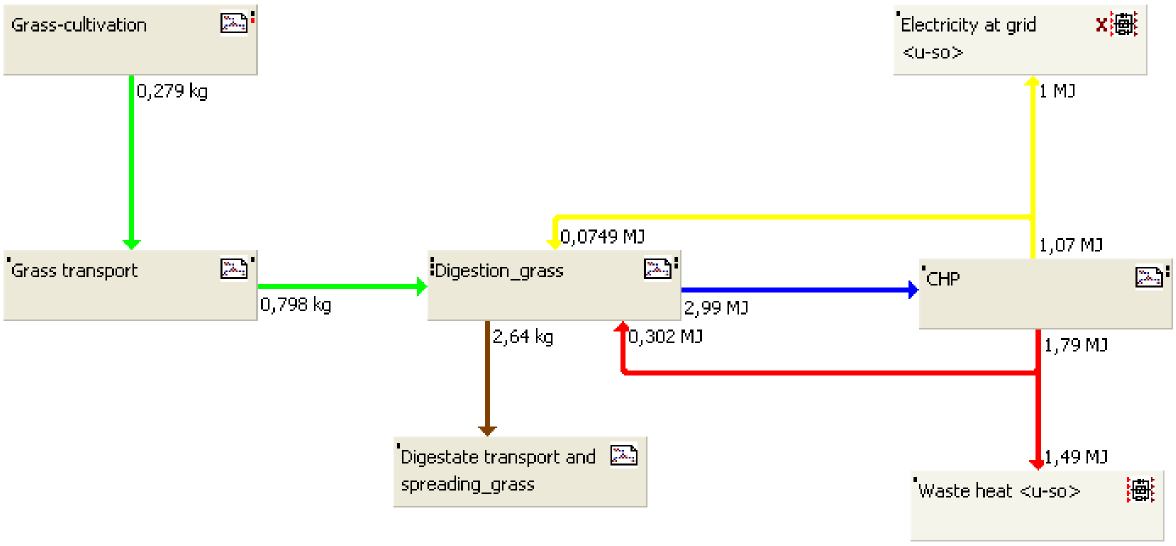


Figure 25 – Pathway III-A[13]

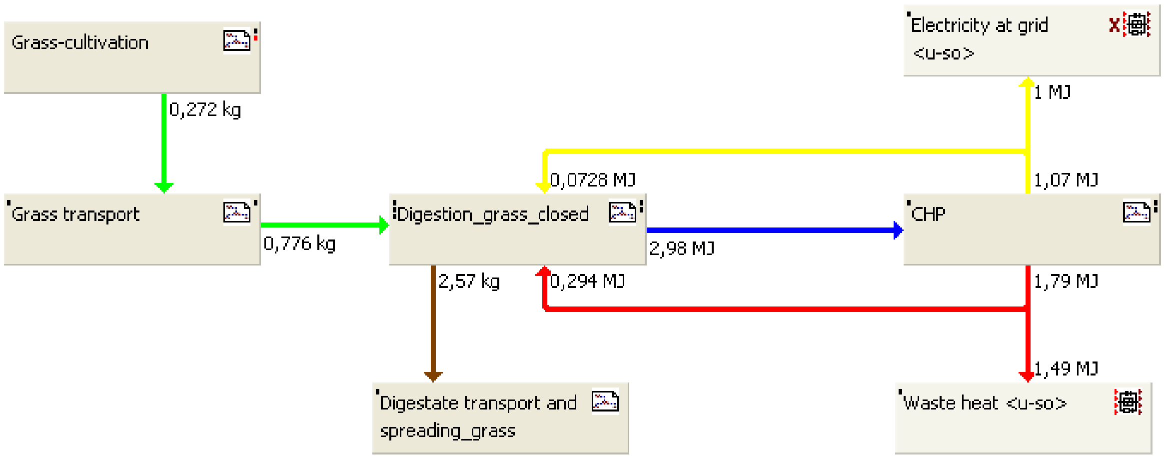


Figure 26 – Pathway III-B

[13] The arrows (and the relative quantities) represent the following flows: Light green: grass silage, Brown: digestate, Blue: biogas, Red: thermal energy, Yellow: electricity

4.3.4 PATHWAY IV: BIOGAS FROM CO-DIGESTION, CHP

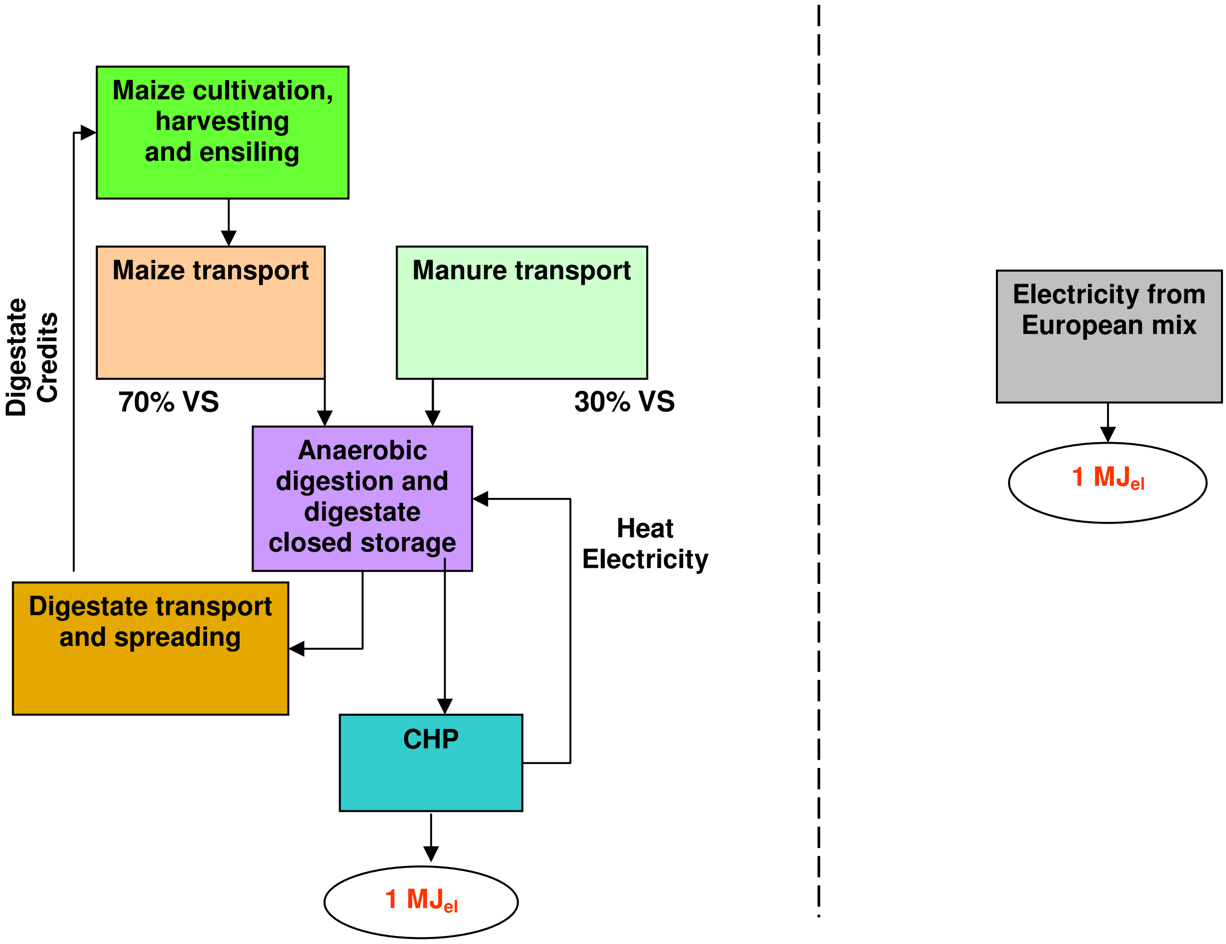


Figure 27 - Biogas from co-digestion of maize and manure vs reference system

Co-digestion is a typical way of combining energy crops and manure in anaerobic digestion. In this work it is assumed a combination of 70% of VS provided by maize and the remaining by manure [19]. Since this energy crop has a higher VS content per kg of raw material than manure, it means that the mixture is composed by maize for the 45% in weight and by manure for the 55%.

In this study it is assumed that no significant synergies exist in the co-digestion of maize and manure, thus the emissions for this pathway are obtained by a simple weighted average of the emissions by single-feedstock pathways.

Each process concerning manure accounts for 55% of the total emissions in phase of biogas production and digestate management, while the remaining 45% is attributed to maize silage. The following picture allows to better understand the way in which this pathway is built.

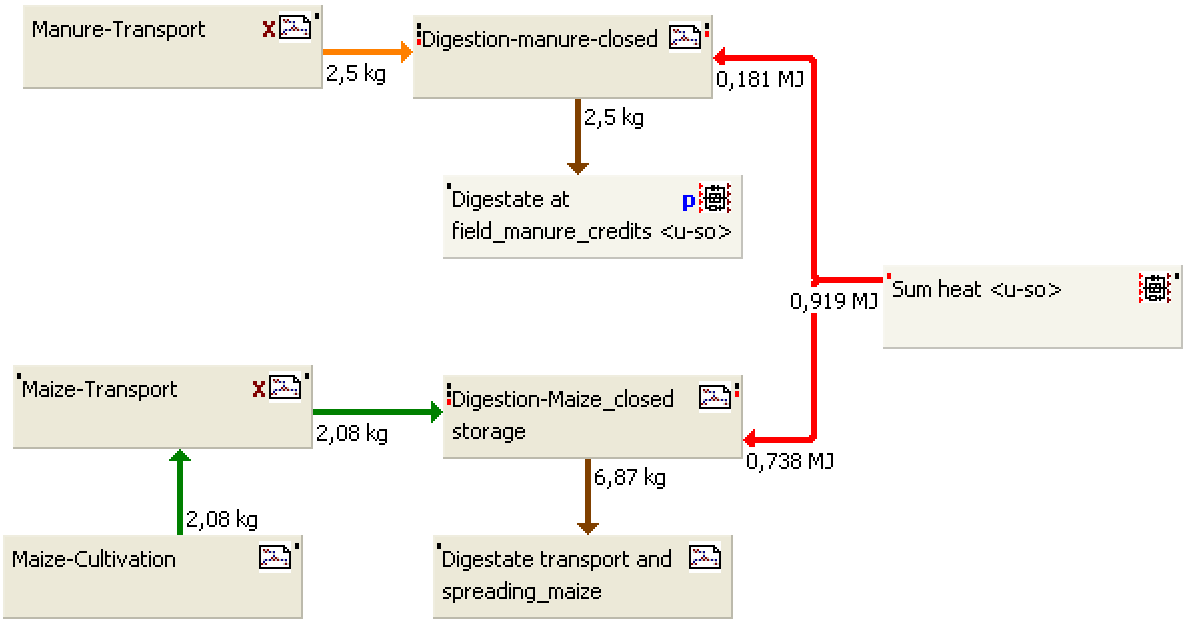
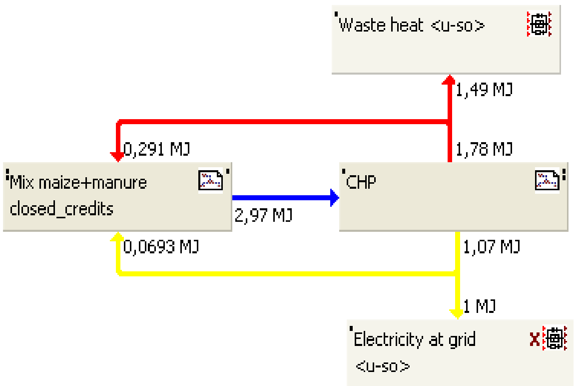


Figure 28 – Example of the construction of co-digestion processes with GaBi software[14]

In this pathway, the reference system accounts only for the emissions due to electricity production because the avoided emissions linked to undigested manure management are discounted in the biogas system and then already calculated as credits. Pathway IV-A corresponds to open storage of digestate while IV-B to the closed one.

4.3.4.1 Results with GaBi software



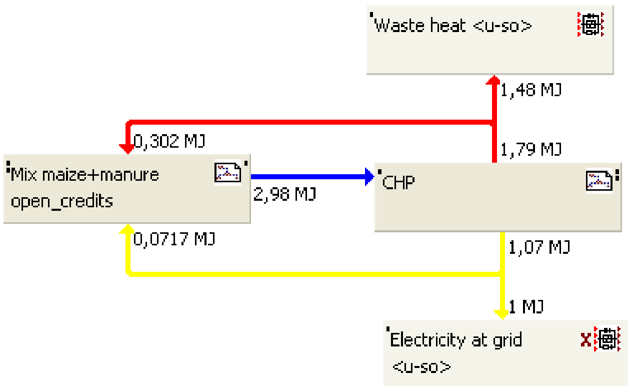


Figure 29 – Pathway IV-B

Figure 30 – Pathway IV-A[15]

[14] The arrows (and the relative quantities) represent the following flows: Green: maize silage, Orange: manure, Brown: digestate, Blue: biogas, Red: thermal energy

[15] The arrows (and the relative quantities) represent the following flows: Blue: biogas, Red: thermal energy, Yellow: electricity

4.3.5 PATHWAY V: BIOGAS FROM MAIZE, UPGRADING

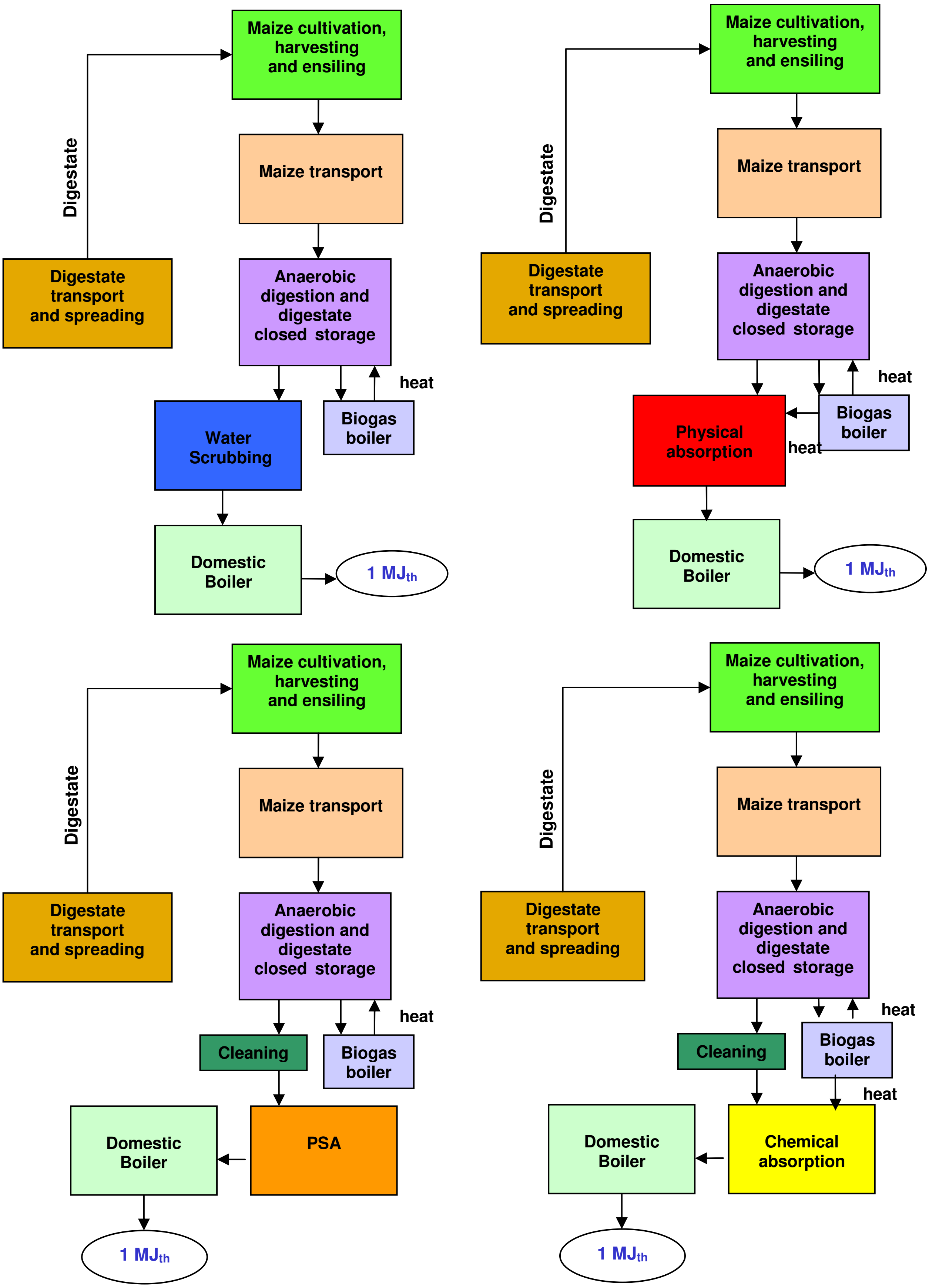


Figure 31 - Biogas from maize used as biomethane, different upgrading technologies

The upgrading phase has already been detailed in Paragraph 4.2.7 and no specific requirement for maize is needed. Only the results of the pathways for closed storage are here visualised.

It is important to underline that considering the open storage means that more maize silage is requested in input, but concerning the utilisation of biogas no differences appear.

For every upgrading technique, the reference system accounts for the production of 1 MJ of thermal energy.

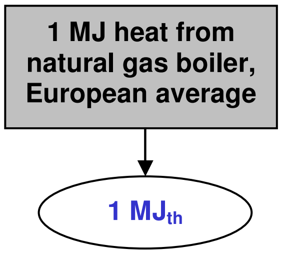


Figure 32 – Reference system of upgrading pathways

4.3.5.1 Results with GaBi software

The mass and energy balances calculated by the software show that in order to produce 1 MJ of thermal energy different amounts of feedstock are required, depending on the efficiency of the specific upgrading technology. Also, various energy and heat requirements are visualised.

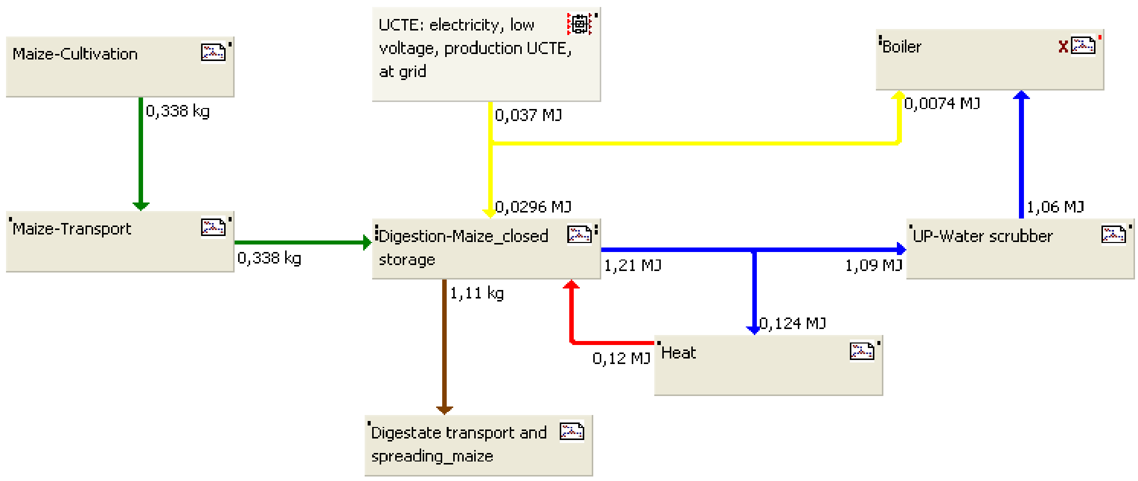


Figure 33 – Maize digestion, closed storage, Water scrubbing[16]

[16] The arrows (and the relative quantities) represent the following flows: Green: maize silage, Brown: digestate, Blue: biogas/biomethane, Red: thermal energy, Yellow: electricity

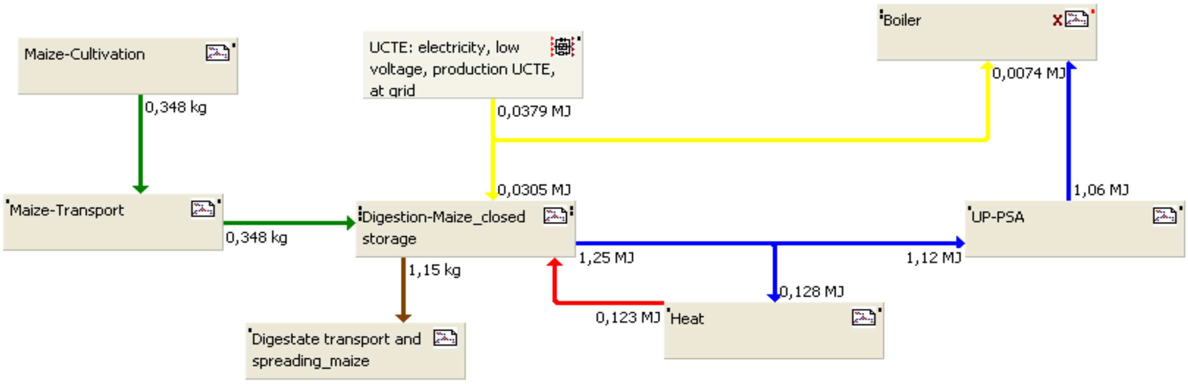


Figure 34 – Maize digestion, closed storage, PSA

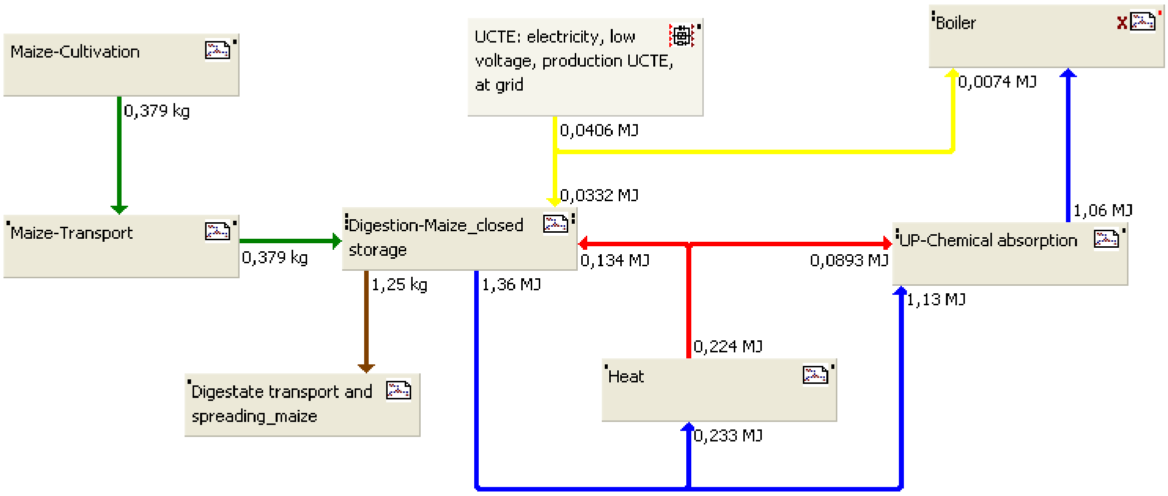


Figure 35 – Maize digestion, closed storage, Chemical absorption

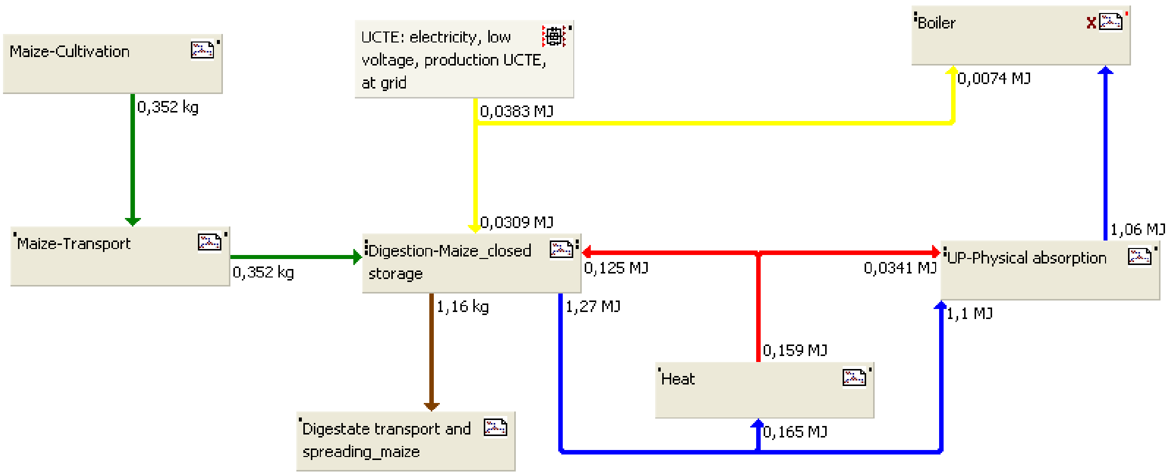


Figure 36 - Maize digestion, closed storage, Physical absorption

4.3.6 Upgrading: the other feedstocks

Mass and energy flows are calculated with GaBi software for all the pathways concerning the upgrading of biogas obtained from AD of manure (Pathway VI), grass (Pathway VII) and in co-digestion of manure and maize (Pathway VIII), both in case of closed and open storage, but are not represented in this report.

4.4 LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION: THE RESULTS

In this Paragraph the results of the Life Cycle Inventory of the pathways introduced earlier are described are analysed with the LCIA methods suggested by the ILCD.
GaBi software automatically classifies emissions and resources consumption, which occur inside the boundaries identified, in the impact categories chosen. The emissions linked to a category are converted into reference units with characterisation factors that are expressed in the characterisation method selected.
No optional operations are done: thus these results are expressed in terms of environmental impacts that could potentially be caused by biogas systems.

It is important to underline that it is possible to compare only pathways with the same functional unit. Therefore, results are presented separately for CHP and upgrading pathways without any comparison between the two.

Concerning the upgrading pathways, results for closed storage only are reported, since it is interesting to explain which technology causes the lowest impact on climate change in combination with the best digestion practice that will be demonstrated to be the utilisation of a closed tank. In fact, the process of biogas production, and also digestate management, does not change according to biogas utilisation and thus consideration expressed for CHP pathways are valid for upgrading too.

For simplicity, the scenarios considering manure as a feedstock include methane, nitrous oxide and ammonia credits and avoid the mechanical transport and spreading of the digestate, in order to be compared with the reference systems consisting only of electricity/heat production. A sensitivity analysis will underline the different results found if the alternative fate of undigested manure is ignored.

The contribution analysis is also done in this section: for each impact, the processes and the chemical compounds that are mostly responsible for the impacts are identified and underlined.

4.4.1 Climate change

The impact on climate is evaluated using the IPCC model implemented in CML method (*CML2001 - Nov. 09, Global Warming Potential (GWP 100 years)).* This model considers the global warming potential of the greenhouse gases (GHG) that are emitted or subtracted during the life cycle. Results are expressed in terms of kg of CO_2-Equivalents.

The CML method is the methodology created by the Centre for Environmental Studies (CML) of the University of Leiden.

4.4.1.1 CHP pathways

In Figure 37, the results in terms of GHG savings are reported.

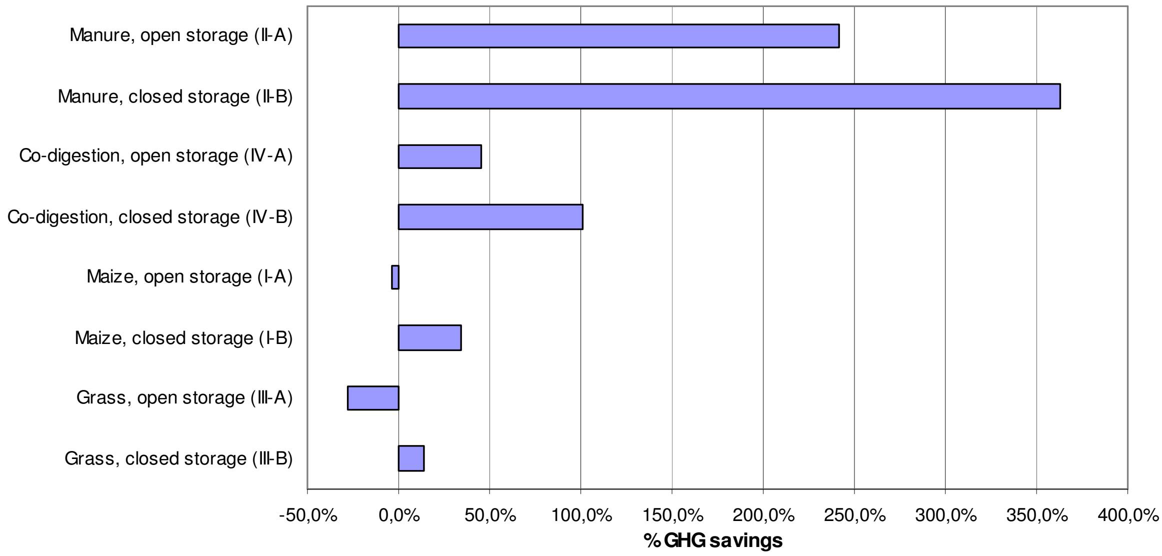


Figure 37 – CHP, GHG savings [%]

- It is clear that the pathways in which the storage tank of the digestate is closed allow saving higher GHG emissions than the corresponding pathways with open storage. This practice should therefore be highly recommended or made mandatory.
- Manure (both in case of closed and open storage) and co-digestion with closed storage of digestate have negative value of emissions because of the account of methane and nitrous oxide credits. In fact, digested manure causes much lower GHG emissions than the undigested material, due also to the conversion of CH_4 (GWP_{100}= 25) into biogenic CO_2 released when biogas is burned. The avoided emissions are so high that all the pathways result in very high GHG savings.
- Grass and maize with open storage tank have negative values in terms of GHG savings. This is due to the higher emissions in the intensive cultivation of the plants. Silage grass farming is even more intensive than maize production. Using a closed storage tank is enough to make the pathways sustainable from this point of view. In Figure 38 the contribution of the closed storage in reducing GHG emissions is underlined (the emissions due to the digestate

storage are included in the process phase *Digestion*). Higher emissions in cultivation are due to the lower energy yield of grass production per hectare, since the similar yields of methane production mean that to obtain the same amount of biogas a comparable mass of feedstock is required in input to the digester.

	Emissions [gCO_2-Equiv./MJ_{el}]	GHG savings [gCO_2-Equiv./MJ_{el}]	Percentage of GHG savings
Reference system	135,2	-	-
Grass, closed storage (III-B)	116,1	19,2	14,2%
Grass, open storage (III-A)	172,6	-37,4	-27,6%
Maize, closed storage (I-B)	89,5	45,7	33,8%
Maize, open storage (I-A)	140,1	-4,8	-3,6%
Co-digestion, closed storage (IV-B)	-0,8	136,1	100,6%
Co-digestion, open storage (IV-A)	74,0	61,2	45,3%
Manure, closed storage (II-B)	-355,4	490,6	362,8%
Manure, open storage (II-A)	-191,1	326,4	242,3%

Table 37 – Results for GWP 100, CHP

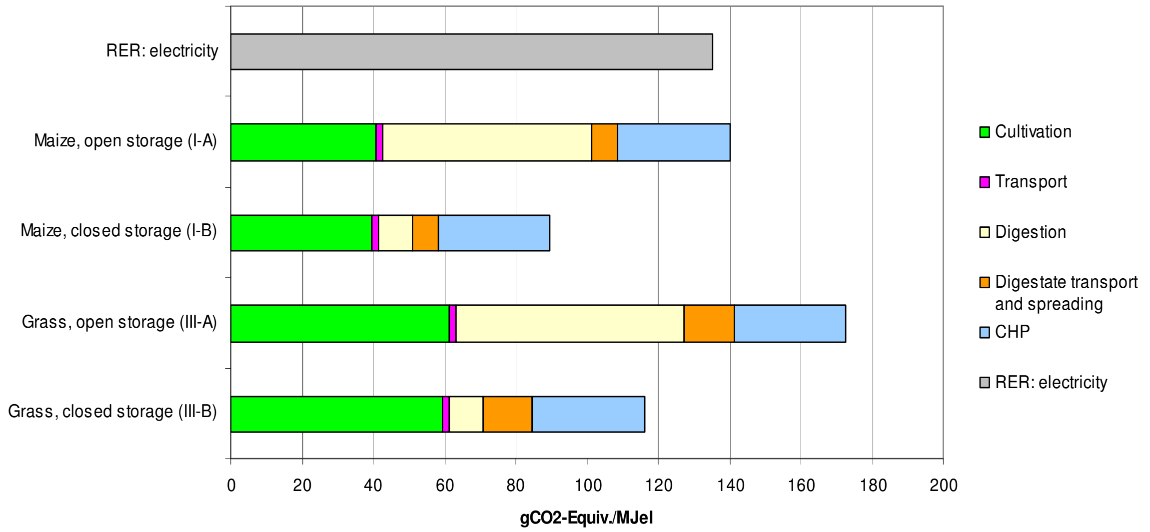


Figure 38 – Contribution of the processes in GHG emission, CHP [gCO_2-Equiv./MJ_{el}]

- Concerning the net contribution of the different GHG emitted, results are reported in Figure 39. While the production of electricity in the reference system emits mainly fossil carbon dioxide, biogas scenarios show the important role of methane and nitrous oxide. It must to be remembered that biogenic carbon dioxide both captured during the plants growth and released during biogas production and utilisation is not accounted for.

The share of the other GHG gases, such as the NMVOC, is negligible.

The contribution of nitrous oxide is relevant for grass silage because of higher emissions in cultivation than maize due to higher nitrogen fertiliser in input.

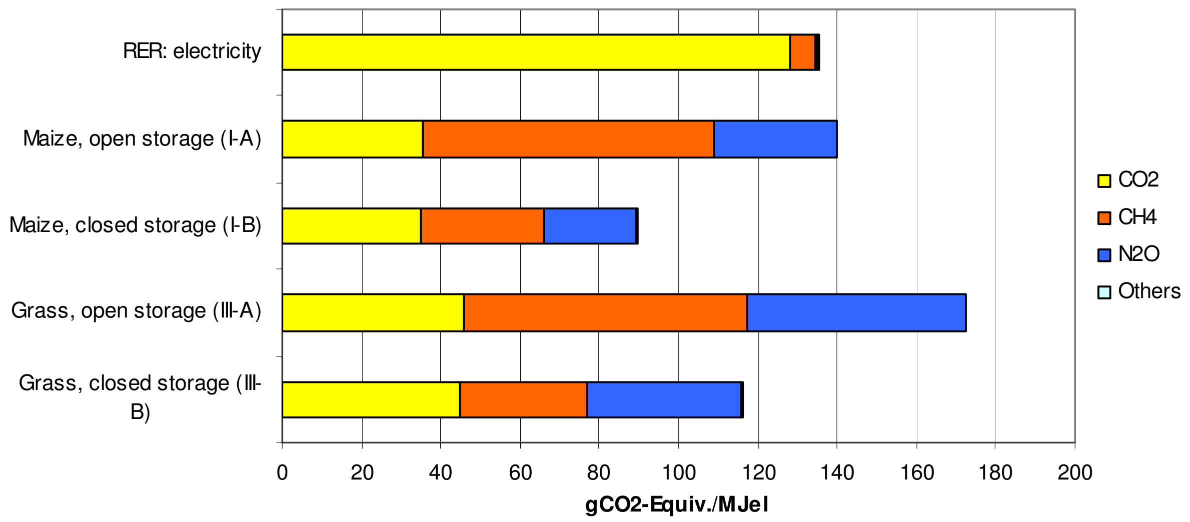


Figure 39 – Contribution of the GHG to the GWP 100, CHP [gCO_2-Equiv./MJ_{el}]

4.4.1.2 Upgrading pathways

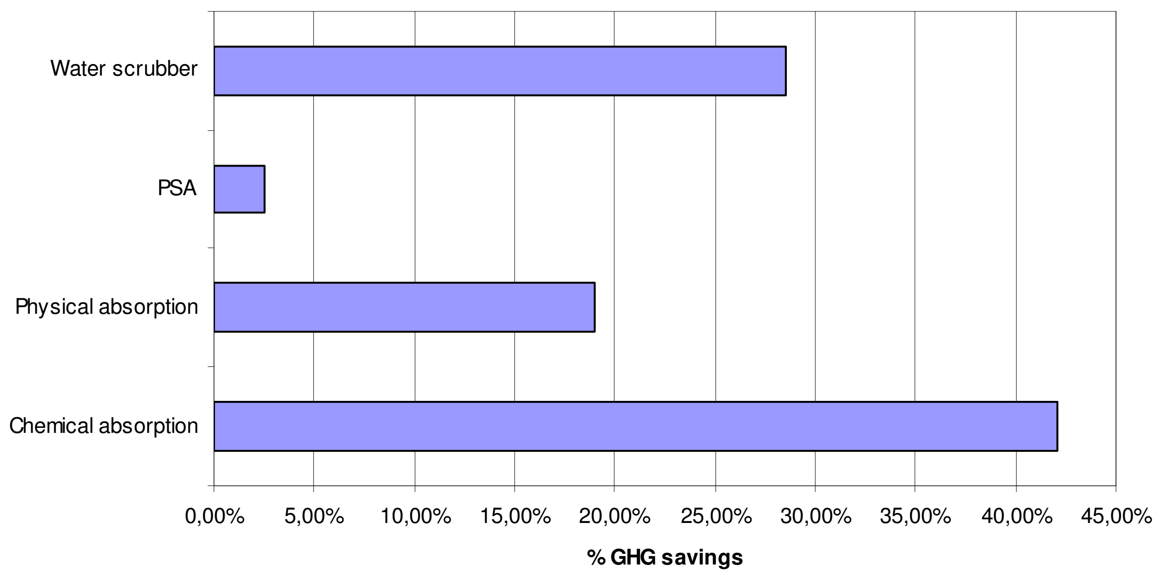


Figure 40 – Upgrading, maize closed storage, GHG savings [%]

- The upgrading technology that allows for higher GHG savings is chemical absorption, as shown in Figure 40 for maize digestion with closed storage tank, followed by water scrubbing, physical absorption and PSA. This clearly depends on the different percentage of methane that is found in the off-gas that is released in the atmosphere. Figure 41 shows that since the phases of feedstock supply, biogas production and digestate management are similar, different emissions are due to the upgrading technique itself. Figure 42 finally better illustrates that methane is the GHG responsible for the higher impacts of PSA, which is the technology that has the highest CH_4 leakages.

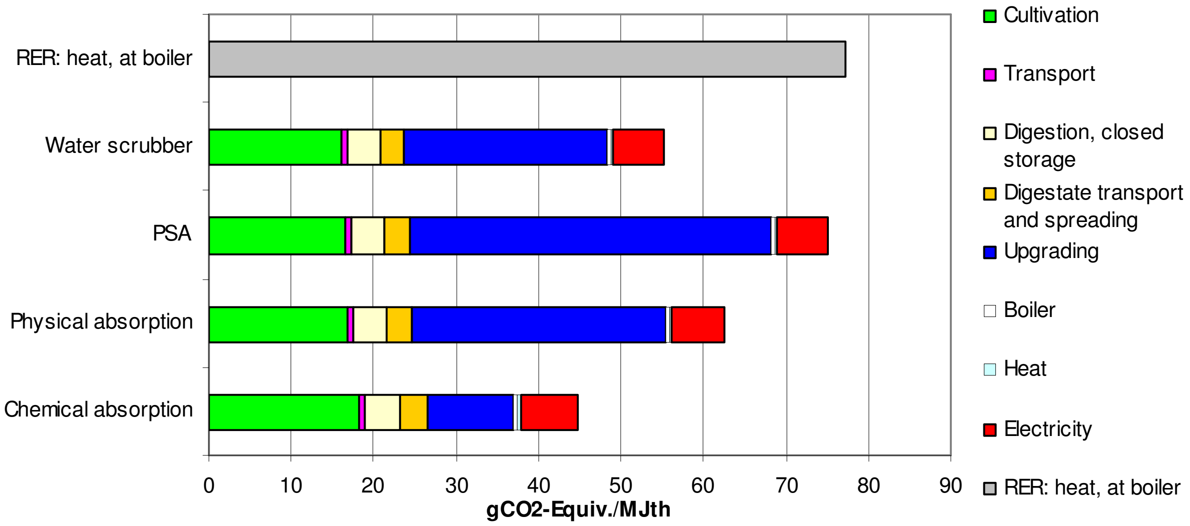


Figure 41 - Contribution of the processes in GHG emission [gCO_2-Equiv./MJ_{th}], maize closed storage, upgrading

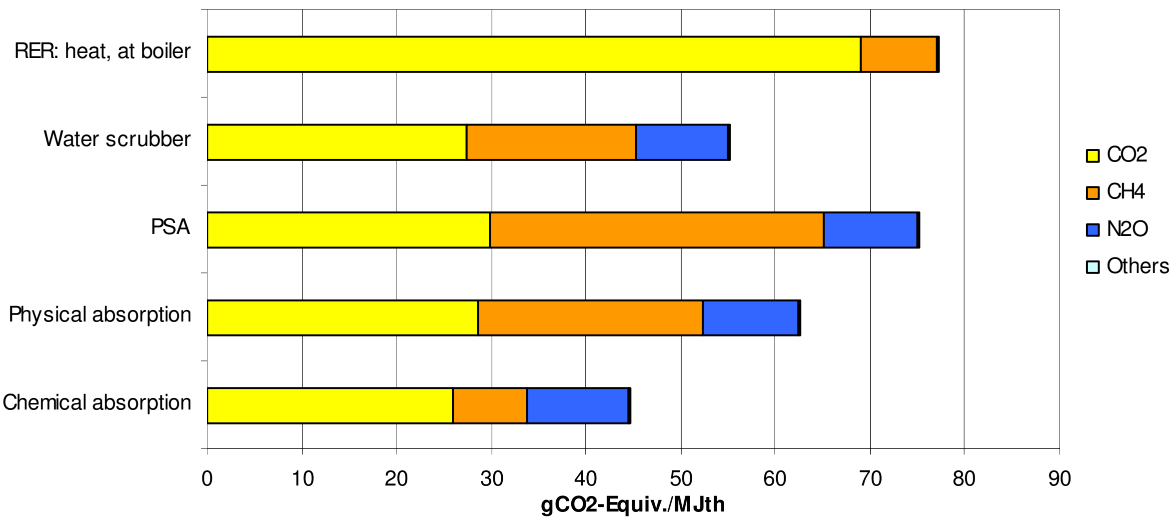


Figure 42 - Contribution of the GHG to the GWP 100, CHP [gCO_2-Equiv./MJ_{th}], maize closed storage, upgrading

Table 38 shows GHG savings for all the feedstocks considered in the study.

- In the worst case (grass silage with PSA) the pathway generates more emissions than the reference system.
- Manure and co-digestion have the highest savings thanks to credits.

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	26,4%	4,3%	-11,9%	14,5%
Maize, closed storage	42,1%	18,9%	2,6%	28,5%
Co-digestion, closed storage	96,4%	69,4%	52,5%	76,9%
Manure, closed storage	310,5%	268,1%	249,1%	267,5%

Table 38 – Results for GWP 100, upgrading, GHG savings [%]

4.4.2 Ozone depletion

This impact category considers the gases that threaten the stratospheric ozone layer. The ozone depletion potential is evaluated with the WMO (World Meteorological Organisation) model implemented in the CML method (*CML2001 - Nov. 09, Ozone Layer Depletion Potential (ODP, steady state)*) [71]. Results are expressed in terms of kg of R11-Equivalents. R11 is trichlorofluoromethane, a halogenate organic NMVOC. This method considers the emissions of halogenated NMVOC to air.

4.4.2.1 CHP pathways

- Little differences are found between pathways with open and closed storage tank: the typical emissions of digestate (methane, nitrous oxide and ammonia) do not have ozone depletion potential. For this impact, biogas production and utilisation is always sustainable compared to the reference system, even if for little percentages.

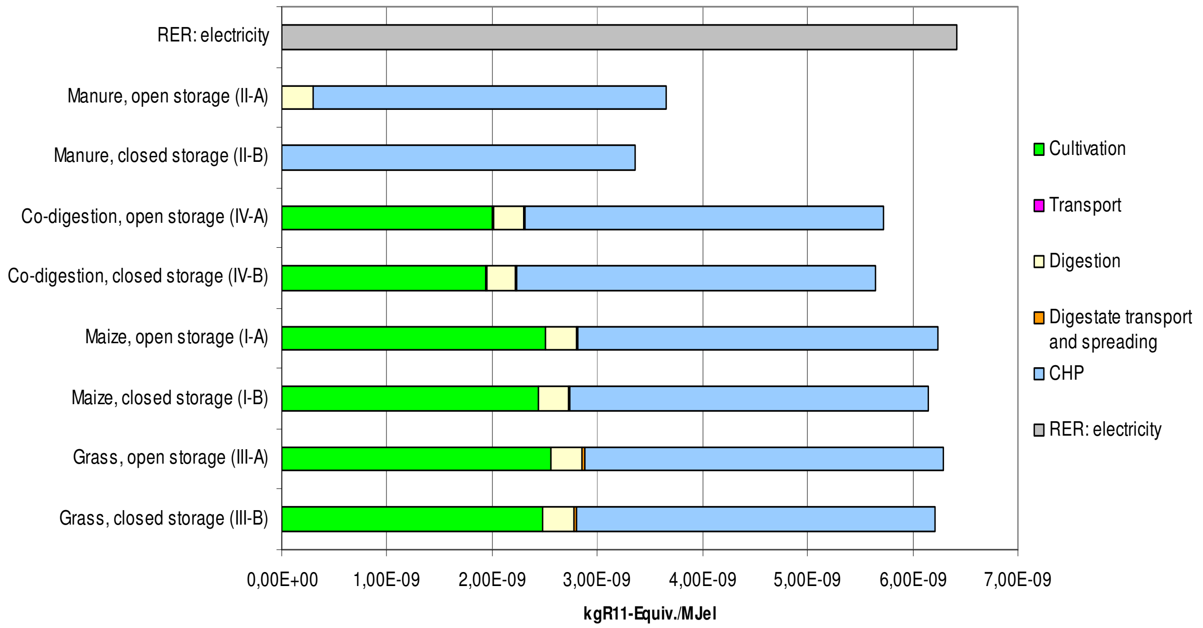


Figure 43 – CHP, Results for ozone depletion potential [kgR11-Equiv./MJ_{el}], contribution of the processes

- Each pathway has similar emissions in CHP processes. The main responsible for ozone depletion is Halon 1301 (97,5% of the kgR11-Equiv. in CHP process) linked to diesel production.
- The presence of energy crops as feedstocks causes high emissions because of the additional cultivation phase, in which Halon 1301 gives the main contribution (between 84,2% and 85,2% of the total kgR11-Equiv.).

4.4.2.2 Upgrading pathways

The upgrading processes allow high savings because the reference system has relevant emissions in terms of kgR11 equivalents (mainly Halon 1211 that derivers from the distribution via pipeline of natural gas produced in Russian Federation). No relevant differences are found between the upgrading technologies.

It is evident that for the pathways using residues (and thus with no cultivation phase) the savings are even higher.

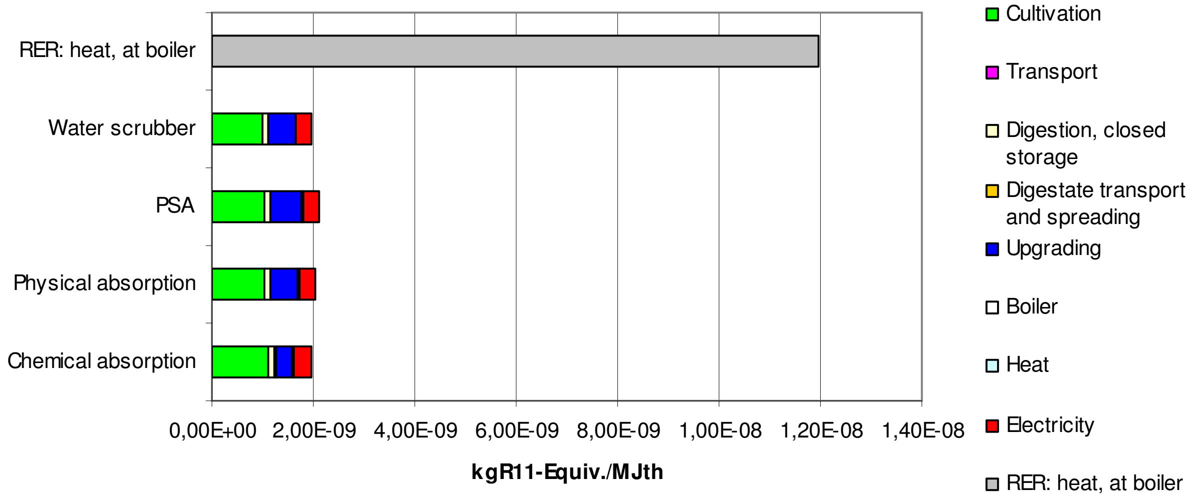


Figure 44 - Upgrading, Results for ozone depletion potential [kgR11-Equiv./MJ_{th}], contribution of the processes, maize closed storage

4.4.3 Human toxicity

Human toxicity is evaluated using the USETox model developed by a task force of the United Nations Environment Program (UNEP) with the Society of Environmental Toxicology and Chemistry (SETAC) (*USETox2008, Human toxicity*). The model considers the chemical fate and human exposure and expresses the increased number of cases of diseases (both cancer and non cancer) [71]. The toxicity according to this method is caused by heavy metals, organic and inorganic emissions to air, to fresh water and to sea water, and pesticide presence in agricultural and industrial soils.

4.4.3.1 CHP pathways

In the production of electricity, the main responsible for human toxicity is formaldehyde (methanal) that is a by-product of incomplete combustion of hydrocarbons and therefore released to air. Formaldehyde emitted from the CHP device alone is responsible for more than 99,6% of the emissions. The little difference between the feedstocks is due to the pesticides used in cultivation. In particular, glyphosate and metolachlor apply in maize cultivation are more significant than asulam utilised in grass farming.

	Emissions [cases/MJ$_{el}$]
RER: electricity	1,04E-12
Grass, closed storage (III-B)	2,81E-10
Grass, open storage (III-A)	2,82E-10
Maize, closed storage (I-B)	2,82E-10
Maize, open storage (I-A)	2,82E-10
Co-digestion, closed storage (IV-B)	2,81E-10
Co-digestion, open storage (IV-A)	2,81E-10
Manure, closed storage (II-B)	2,76E-10
Manure, open storage (II-A)	2,77E-10

Table 39 - Results for human toxicity, CHP [cases/MJ$_{el}$]

4.4.3.2 Upgrading pathways

In the upgrading process, the potential damages are due mainly to the emission of formaldehyde that is released during the combustion of the methane in the boiler (98,9% of the cases for *Boiler* process). The same amount of formaldehyde is released in the reference system. However, little amounts of dangerous elements in different processes in biogas pathways make them less sustainable.

Using feedstocks that requires low/no emissions in cultivation means to have lower emissions than maize pathways, but still a little higher than the reference system (i.e. 6% higher in manure pathways).

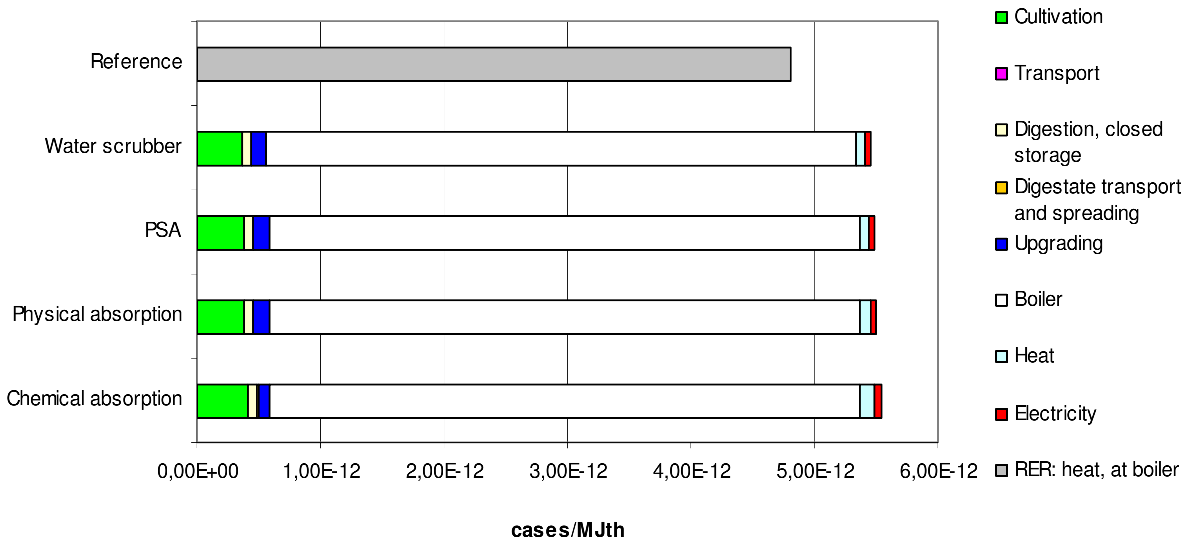


Figure 45 - Upgrading, Results for ozone depletion potential [kgR11-Equiv./MJ$_{th}$], contribution of the processes, maize closed storage

4.4.4 Particulate matter/Inorganics

For this impact, ILCD recommends to consider the fraction of particulate matter below 2,5 µm [71]. The method chosen among the available into GaBi software calculates the results in terms of kg PM2.5-Eq. to air, considering the emissions of dust and of different inorganic species that have a potential of particulate material formation: SO_2, NOx, N_2O, NO_2, CO, NH_3.

4.4.4.1 CHP pathways

This impact shows different results depending on the specific pathways.

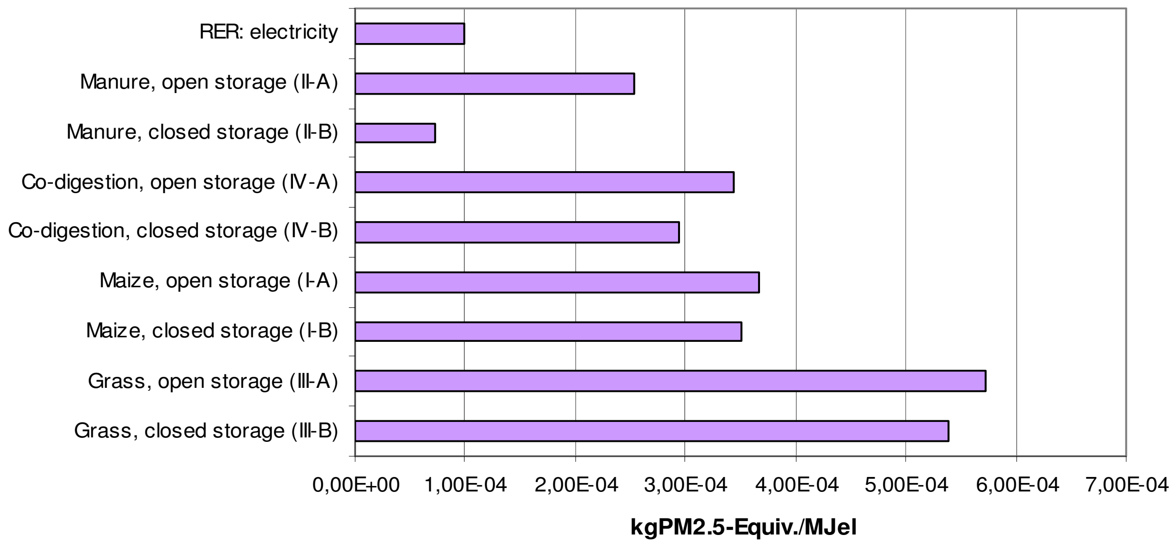


Figure 46 - CHP, Results for particulate matter formation [kgPM2,5-Equiv./MJ_{el}]

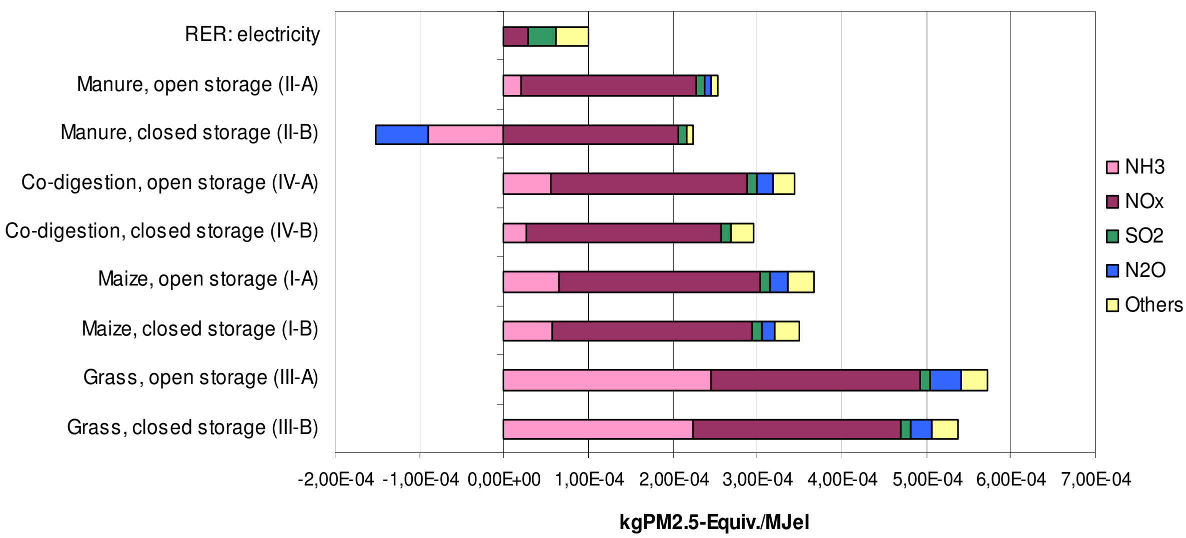


Figure 47 - Contribution of different gases to particulate matter formation, CHP [kgPM2,5-Equiv./MJ_{el}]

- All the pathways result in relevant particulate formation potential due to the emissions of nitrogen oxides in the phase of combustion in the CHP engine (about 0,00022 kgPM2.5-Equiv./MJ_{el})
- In pathways with the digestion of grass, the high amount of kgPM2.5-Equiv./MJ_{el} is caused by the emissions of ammonia in cultivation.
- In the case of open storage, the higher values are linked both to ammonia released during the storage (for manure pathways), and in the request of more biomass in input to be cultivated (in energy crop pathways)
- Even if in manure pathways high quantity of ammonia are released in both closed and open storage cases, credits allow to have low net impacts. With a closed storage tank, net ammonia and nitrous oxide emissions are even negative and allow reducing the total particulate formation potential mainly due to nitrogen oxides.

4.4.4.2 Upgrading pathways

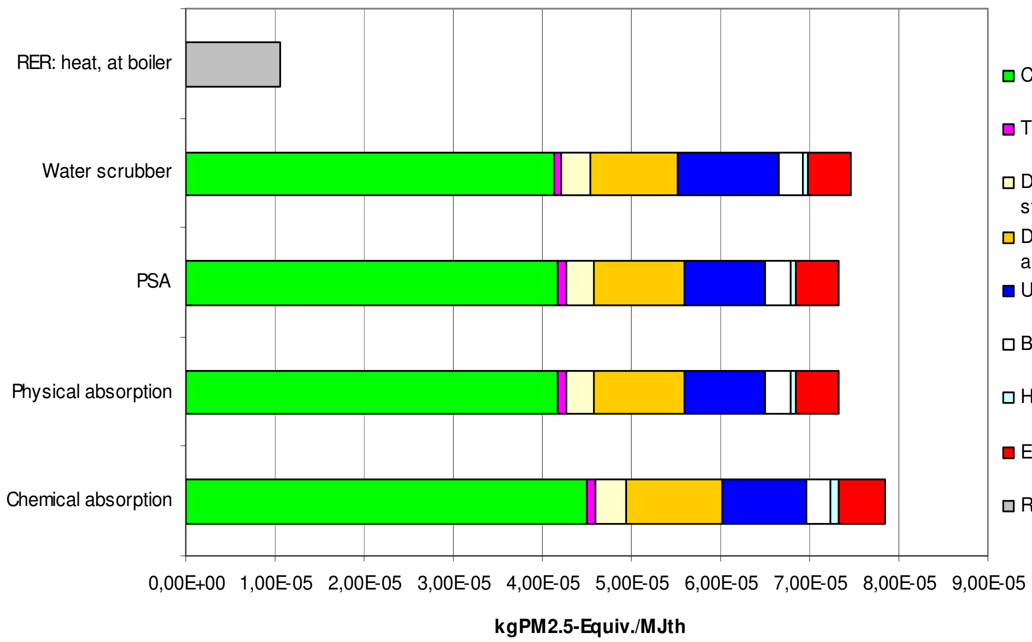


Figure 48 - Upgrading, Results for particulate matter formation [kgPM2,5-Equiv./MJ_{th}], contribution of the processes, maize closed storage

Again, the process more responsible for this impact is cultivation because of the emissions of ammonia. The other processes play a significant role since emissions of NH_3, NO_x, SO_2 and thin dust occur. The emissions in these processes do not change significantly with the specific upgrading technique.

Considering the other feedstocks, results are presented in Table 40 in terms of percentage of increased emissions. Since it has been shown that there is no difference between the upgrading technologies, the remarks made for CHP utilisation are valid.

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	1445%	1339%	1343%	1280%
Maize, closed storage	638%	590%	602%	562%
Co-digestion, closed storage	395%	364%	378%	345%
Manure, closed storage	-560%	-522%	-498%	-505%

Table 40 - Results for particulate matter formation, upgrading, % of the emissions of the reference system

When cultivation is required, chemical absorption causes higher impacts than the other technologies because a higher amount of biomass is required to reach the functional unit. In fact, even though the upgrading technology itself has the highest efficiency (low methane leakage) the requirement of process heat and the low efficiency of the cleaning phases require a higher amount of biogas in output of the digester.

4.4.5 Ionising radiation

The chosen method is *ReCiPe Midpoint - Ionising radiation* that calculates the kilograms of U_{235} equivalents.
ReCiPe methodology for LCIA was created by a joint group of Dutch universities and research centres [75].

4.4.5.1 CHP pathways

The production of electricity in the reference system causes the emissions of 35523 kgU_{235}-Equiv./MJ_{th} This value is much higher than the radioactive potential calculated for biogas pathways, which present values between 95,3% (grass, open storage) and 98,3% (manure, closed storage) lower. Around 94% of the kgU_{235}-Equiv./MJ_{el} is represented by the isotope C (14), both in biogas and in reference system.
Thus, this impact is negligible. The reason is that the reference system accounts also for the production of electricity from nuclear power plants and from coal and lignite that leave residual radioactive ash material.

4.4.5.2 Upgrading pathways

In case of upgrading, 431 kgU_{235}-Equiv./MJ_{th} are attributed to the reference system while biogas pathway is responsible for higher emissions, as shown in Figure 49. Electricity production from conventional fuels is the most relevant process, corresponding in the picture to the red section and to about 80% of the blue one, because also in the upgrading phase electricity is necessary (process UCTE: electricity, low voltage, production UCTE, at grid).
Again, C (14) represents 95% of the radiation potential.

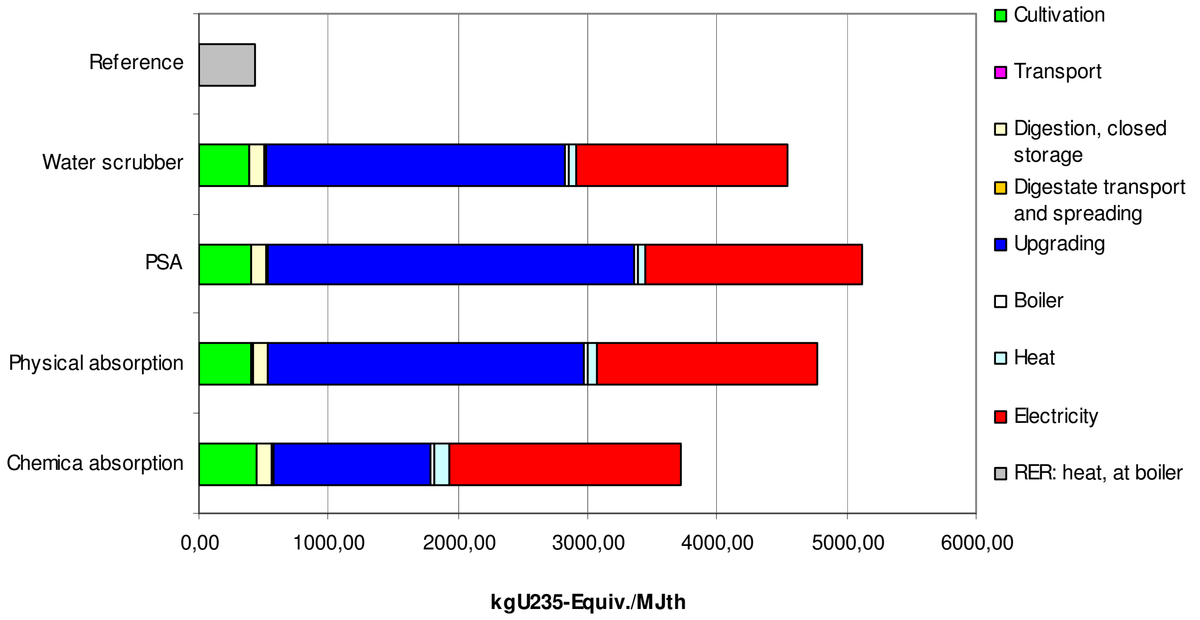


Figure 49 - Upgrading, Results for ionising radiation [kgU_{235}-Equiv./MJ_{th}], contribution of the processes, maize closed storage

4.4.6 Photochemical ozone formation

The method *ReCiPe Midpoint - Photochemical oxidant formation* allows to express the emissions that are responsible of the formation of ozone and other oxidants in the troposphere in terms of kilograms of NMVOC [71]. The compounds considered are inorganic emissions to air such as CO, NO_x, SO_2, the organic NMVOC and methane.

4.4.6.1 CHP pathways

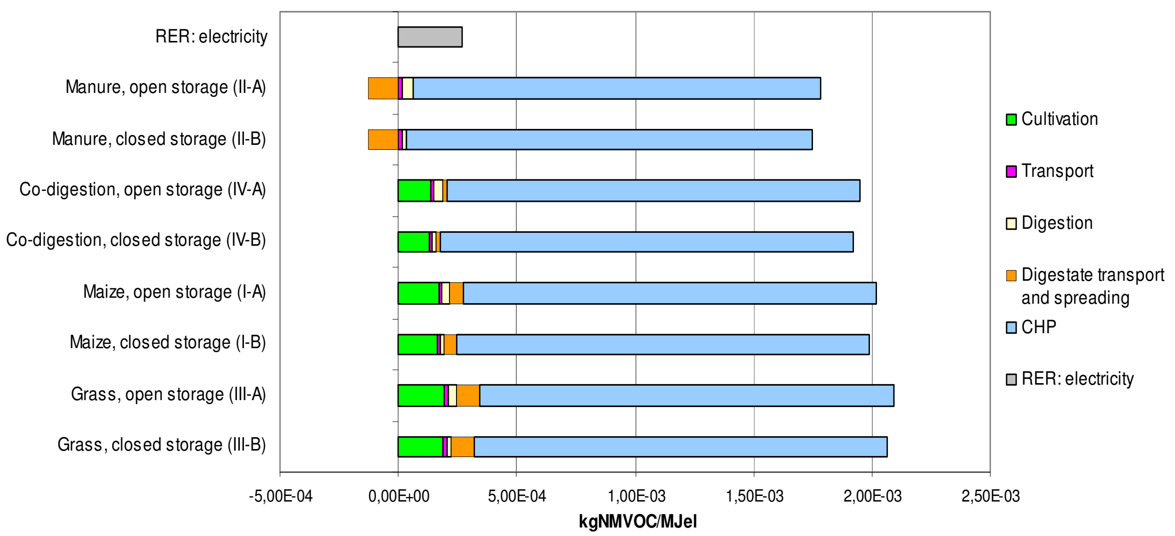


Figure 50 - CHP, Results for photochemical ozone formation [kgNMVOC/MJ_{el}], contribution of the processes

Figure 50 shows that the higher emissions compared to the reference system are mostly due to the combustion in the CHP because of the amount of nitrogen oxides that are released. The missing phase of cultivation and the account of credits give to manure pathways less oxidant formation potential but in general biogas scenarios score worse than the reference system, because of the anti-NO_x techniques in electricity generation of the large-scale plants.

4.4.6.2 Upgrading pathways

- Each process gives a certain contribution to the creation of tropospheric ozone. As a result, also in the upgrading systems the impact is higher than the reference system. Nitrogen oxides have the most important role (between 83,8% and 88,5% of the total $kgNMVOC/MJ_{th}$).

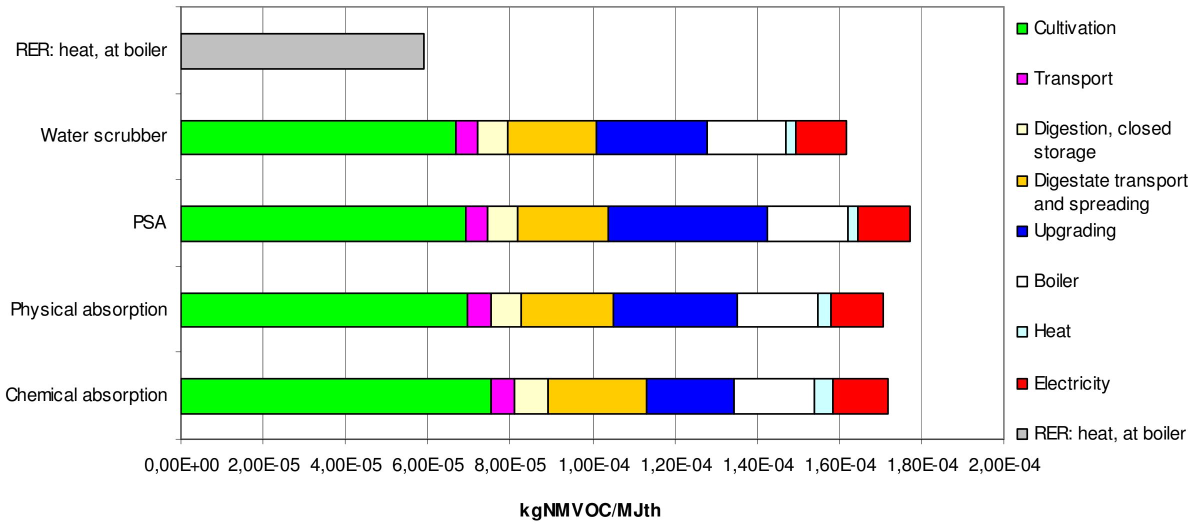


Figure 51 - Upgrading, Results for photochemical ozone formation [$kgNMVOC/MJ_{th}$], contribution of the processes, maize closed storage

- Since the cultivation of grass produces more nitrogen oxides, using this feedstock causes the highest impact. Decreasing the contribution due to cultivation processes and adding credits permit to have lower potential than grass pathways but still higher impacts than the reference system. Only manure digestion allows reducing the impact.

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	247%	240%	251%	223%
Maize, closed storage	191%	188%	200%	174%
Co-digestion, closed storage	136%	138%	149%	125%
Manure, closed storage	-76%	-60%	-46%	-64%

Table 41 - Results for photochemical ozone formation, upgrading, % of the emissions of the reference system

4.4.7 Acidification potential

The acidification potential is expressed in terms of kilograms of sulphur dioxide (SO_2) equivalents. The impact method chosen is *CML2001 - Nov. 09, Acidification Potential* [71].

4.4.7.1 CHP pathways

- Except for the pathway that considers manure digestion and closed storage tank, which benefits of high values of credits for the avoided emissions of ammonia, all scenarios are more potentially harmful than the reference system.
- The most important emissions that contribute to create acidification are ammonia (in cultivation, digestate transport and spreading and digestate storage, if in open air) and nitrogen oxides and sulphur dioxide released during biogas combustion in CHP devices.

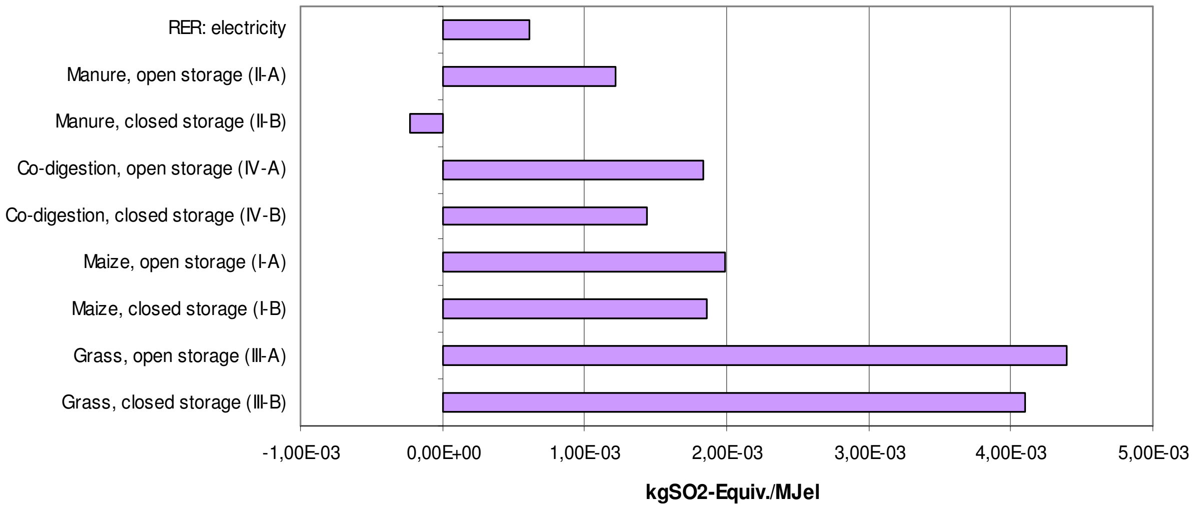


Figure 52 - CHP, Results for acidification potential [kgSO_2-Equiv./MJ_{el}]

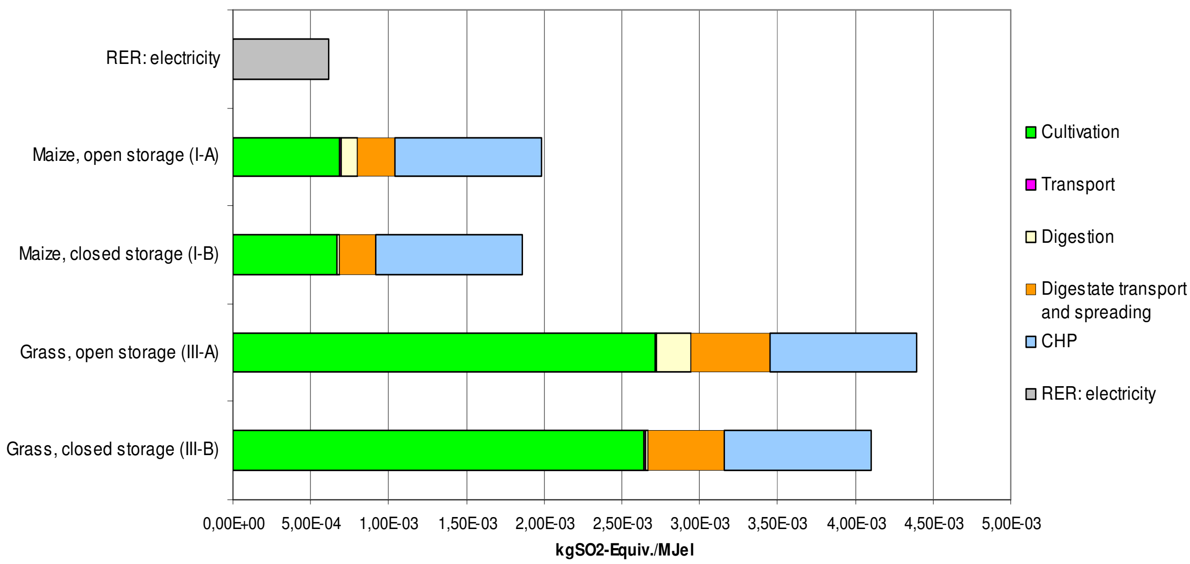


Figure 53 - CHP, Results for acidification potential [kgSO_2-Equiv./MJ_{el}], contribution of the processes

- Keeping the digestate in a closed tank reduces significantly the emissions only in case of manure
- During the cultivation of grass, nearly 4,5 times higher ammonia than maize is released.

4.4.7.2 Upgrading pathways

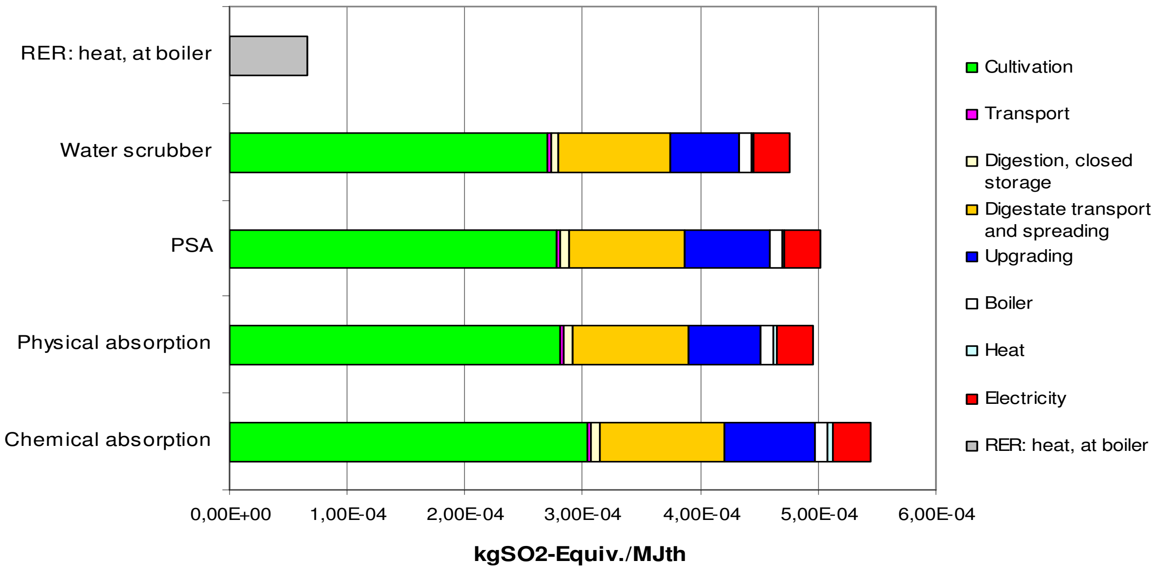


Figure 54 - Upgrading, Results for acidification potential [$kgSO_2$-Equiv./MJ_{th}], contribution of the processes, maize closed storage

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	2258%	2074%	2068%	1985%
Maize, closed storage	719%	645%	654%	614%
Co-digestion, closed storage	423%	370%	383%	351%
Manure, closed storage	-731%	-702%	-678%	-677%

Table 42 - Results for acidification potential, upgrading, increase % of the emissions of the reference system

No differences between the technologies appear. The emissions are higher than the reference system in every case and the most relevant responsible process is cultivation. Results for all feedstocks in terms of percentage referred to the reference system are reported in Table 42. Thanks to the credits, benefits are visualised for the digestion of manure.

4.4.8 Eutrophication

In ReCiPe recommended method, two different systems are analysed with two different models in order to consider the distinction of aquatic receiving environments according to their limiting nutrient: freshwater systems (generally P-limited) and marine water systems (generally N-limited) [32].

The eutrophication potential to freshwater systems is expressed in kgP-Equiv. and it is calculated according to *ReCiPe Midpoint - Freshwater Eutrophication*. It is based on models for European conditions, addresses all aspects of aquatic eutrophication for both airborne and waterborne emissions. It considers only the emissions of phosphate and phosphorus to fresh water, to agricultural soil and to industrial soil [71].

The eutrophication potential to marine coastal systems is expressed in kgN-Equiv. and it is calculated according to *ReCiPe Midpoint - Marine Eutrophication*. It considers only the emissions of ammonia, ammonium, nitrate, nitrogen oxides and nitrogen organic to air and to fresh water [71].

4.4.8.1 CHP pathways for Freshwater Eutrophication

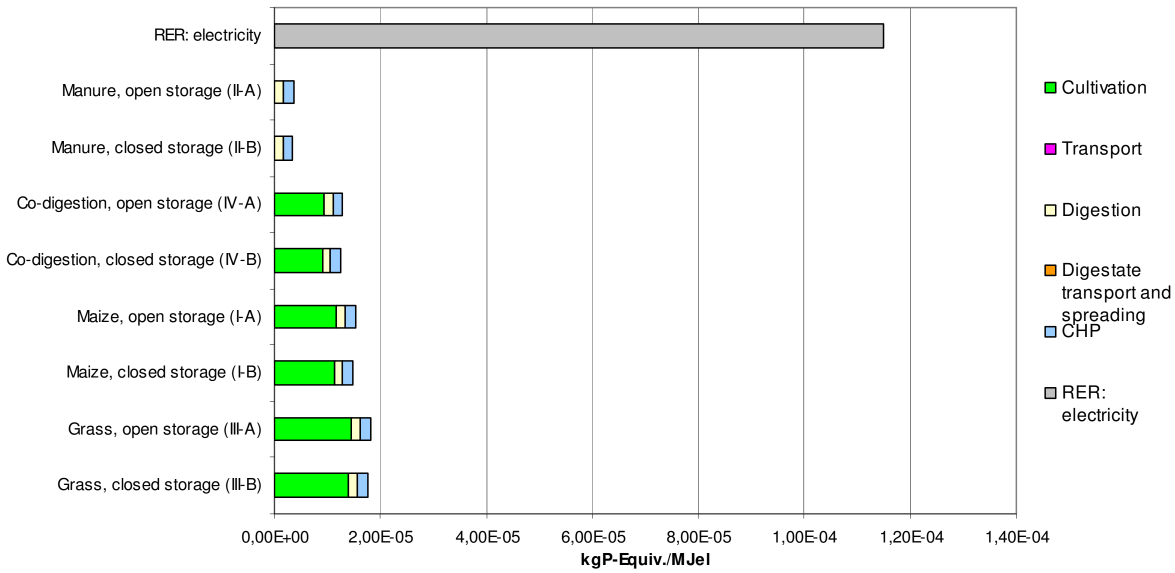


Figure 55 - CHP, Results for freshwater eutrophication [kgP-Equiv./MJ$_{el}$], contribution of the processes

The potential is mainly due to the presence of phosphate in the freshwater. Compared to the reference system, it results negligible.

4.4.8.2 Upgrading pathways for Freshwater Eutrophication

The very low eutrophication potential of the reference system makes biogas pathways unsustainable from this point of view.

The key reason of the higher potential is linked to electricity production that causes the creation of phosphate. It has to be reminded that also *Upgrading* process includes the emissions due to the production of fossil electricity. Its production contributes to more than 75% of the potential of the specific phase (57% in case of chemical absorption, due to the lower energy requirement).

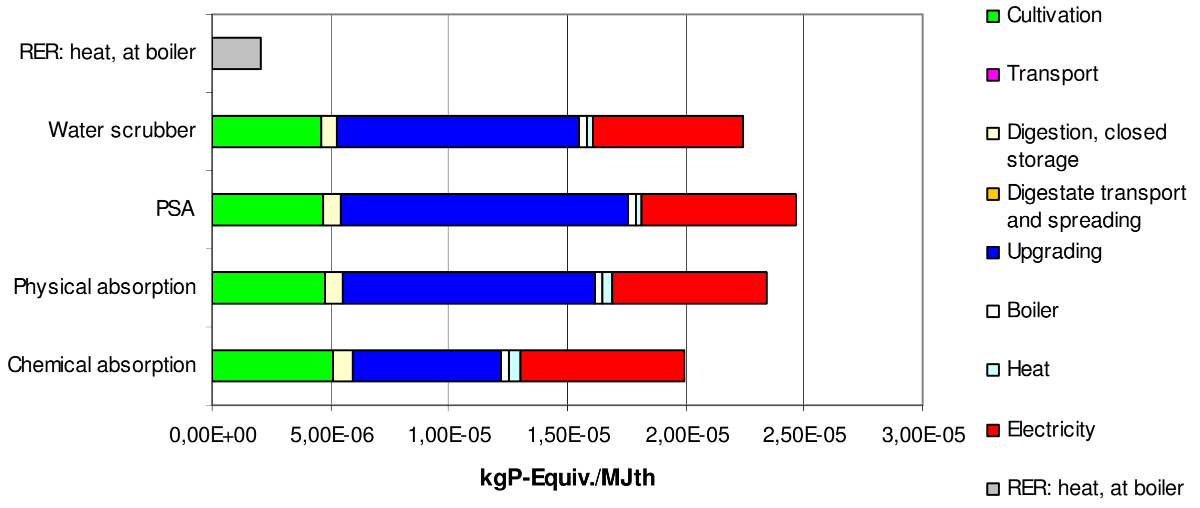


Figure 56 - Upgrading, results for freshwater eutrophication [kgP-Equiv./MJ_{th}], contribution of the processes, maize closed storage

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	895%	1063%	1124%	1013%
Maize, closed storage	824%	997%	1058%	950%
Co-digestion, closed storage	707%	887%	950%	844%
Manure, closed storage	477%	673%	739%	640%

Table 43 - Results for freshwater eutrophication, upgrading, increase % of the emissions of the reference system

4.4.8.3 CHP pathways for Marine Eutrophication

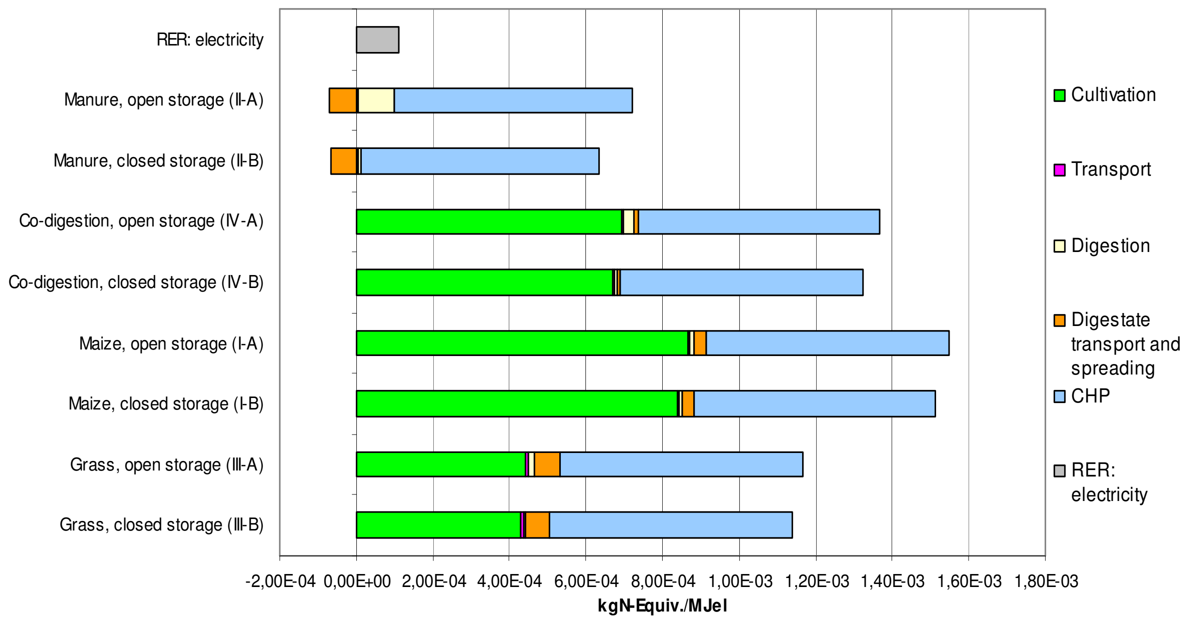


Figure 57 - CHP, Results for marine eutrophication [kgN-Equiv./MJ_{el}], contribution of the processes

Each pathway has a higher impact because of the release of nitrogen oxides in phase of biogas utilisation. The other significant contribution is given by the process of cultivation. Since maize production results in much nitrate leaching to the water system (89% of the impact in cultivation), its importance is higher than in grass farming.

4.4.8.4 Upgrading pathways for Marine Eutrophication

Again, cultivation is the most relevant process for this impact.

Thanks to ammonia credits, manure pathways are responsible for less emission than the reference system.

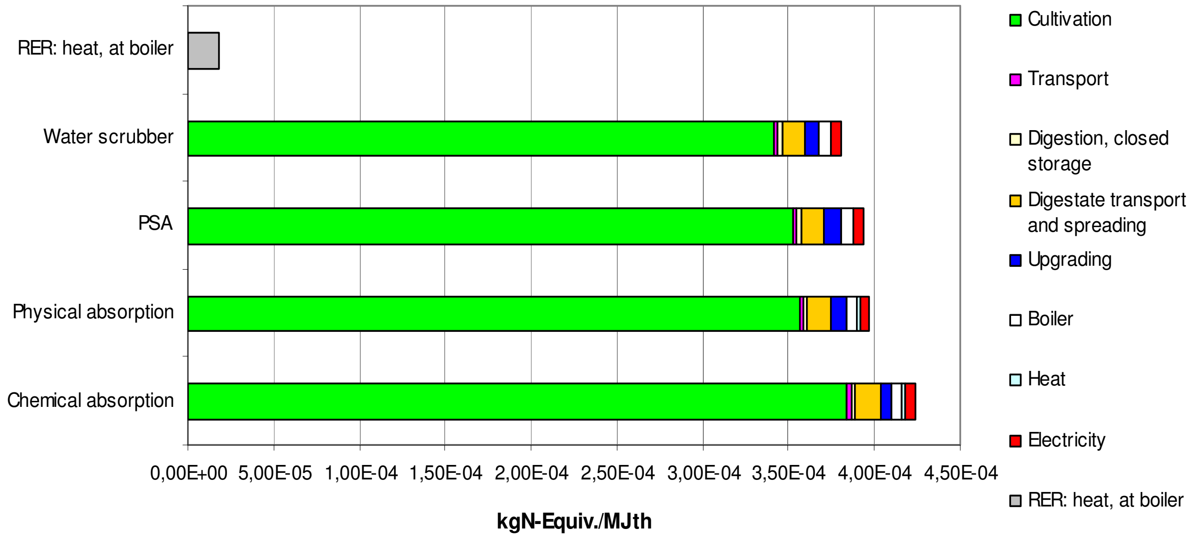


Figure 58 - Upgrading, results for marine eutrophication [kgN-Equiv./MJ_{th}], contribution of the processes, maize closed storage

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	1313%	1232%	1224%	1177%
Maize, closed storage	2281%	2131%	2113%	2039%
Co-digestion, closed storage	1792%	1677%	1664%	1604%
Manure, closed storage	-143%	-120%	-113%	-119%

Table 44 - Results for marine eutrophication, upgrading, increase % of the emissions of the reference system

4.4.8.5 Eutrophication with CML method

The method CML *2001 – Nov. 09 Eutrophication Potential (EP)* considers both N and P contribution. It also provides characterisation factors for organic material emissions to water presented as BOD or COD. Indicator results expressed as PO_4^{3-}-equivalents.

As far as CHP pathways is concerned, only manure utilisation saves emissions thanks to ammonia and nitrous oxide credits. The fact that the other pathways are not sustainable according to this method means that nitrogen emissions are considered to have higher potential than phosphorous compounds.

In cultivation processes, ammonia is the most responsible for grass and nitrate for maize production. In CHP combustion, the release of nitrogen oxides accounts for 92%.

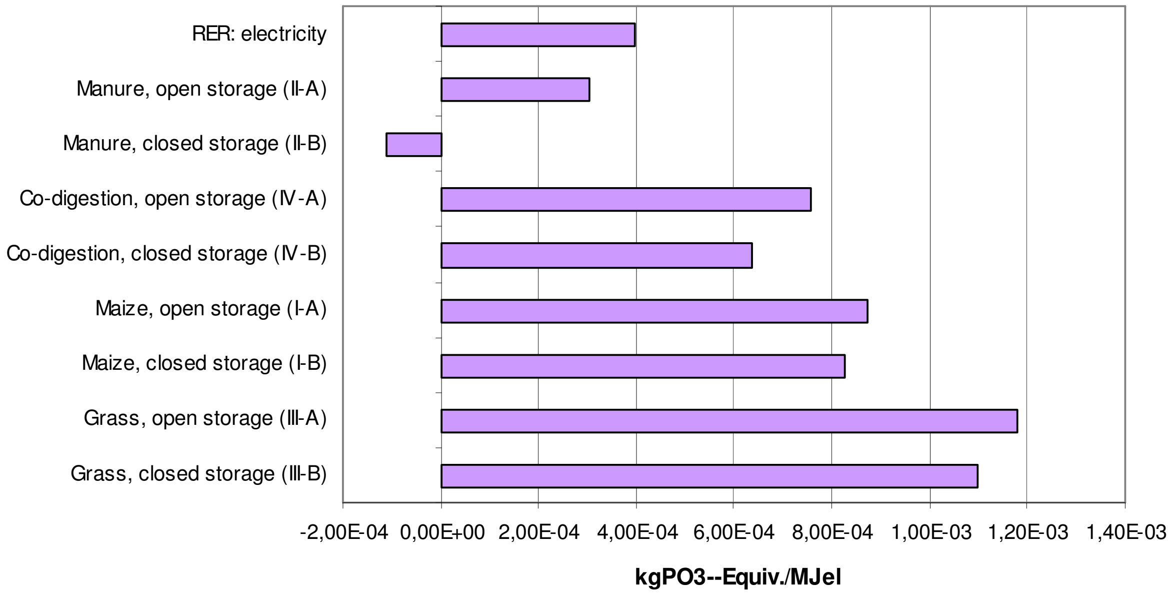


Figure 59 - CHP, Results for eutrophication potential with CML method [kgPO^{3-}-Equiv./MJ_{el}]

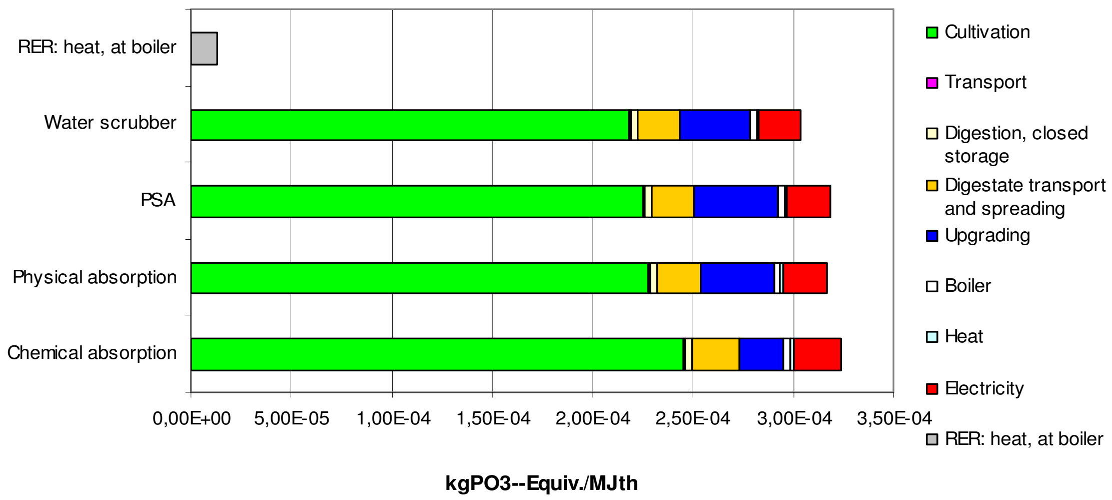


Figure 60 - Upgrading, results for eutrophication potential with CML method [kgPO^{3-}-Equiv./MJ_{th}], contribution of the processes, maize closed storage

In upgrading pathways, as it can be seen in Figure 60, the situation reflects the ReCiPe methods: the high contribution of the cultivation and digestate spreading is due to nitrogen compounds, while the role of electricity is linked to phosphate.

Among the other feedstocks, only manure is able to save emissions thanks to credits.

4.4.9 Freshwater Ecotoxicity

The model chosen to express the ecotoxicity to water predicts the Potentially Affected Fraction of species (PAF) in a cubic meter of environment per day. The method used is *USETox2008, Ecotoxicity* [32]. The toxicity according to this method is caused by heavy metals, organic and inorganic emissions to air, to fresh water and to sea water, and pesticide presence in agricultural and industrial soils.

4.4.9.1 CHP pathways

	Emissions [PAF m^3.day/MJ_{el}]
RER: electricity	7,18E-05
Grass, closed storage (III-B)	7,60E-04
Grass, open storage (III-A)	7,74E-04
Maize, closed storage (I-B)	5,08E-02
Maize, open storage (I-A)	5,23E-02
Co-digestion, closed storage (IV-B)	4,05E-02
Co-digestion, open storage (IV-A)	4,19E-02
Manure, closed storage (II-B)	3,10E-04
Manure, open storage (II-A)	3,12E-04

Table 45 - Results for freshwater ecotoxicity, CHP [PAF m^3.day/MJ_{el}]

In Table 45 it can be seen that all the pathways have higher impact than the reference system, but the scenarios including the cultivation of maize have much higher amounts due exclusively to pesticide utilisation (90%). Grass cultivation requires asulam that creates a significant impact potential but can not be compared to what metolachlor and glyphosate are expected to cause for maize. The other important contribution that makes higher potential in manure pathways for example is provided by nitrogen oxides released during biogas combustion.

4.4.9.2 Upgrading pathways

Emissions [PAF m^3.day/MJ_{th}]	**Chemical absorption**	**Physical absorption**	**PSA**	**Water scrubber**
RER: heat, at boiler	2,08E-05			
Grass, closed storage	2,88E-04	2,73E-04	2,72E-04	2,64E-04
Maize, closed storage	2,32E-02	2,15E-02	2,13E-02	2,06E-02
Co-digestion, closed storage	1,85E-02	1,72E-02	1,70E-02	1,65E-02
Manure, closed storage	8,27E-05	8,26E-05	8,30E-05	8,12E-05

Table 46 - Results for freshwater ecotoxicity, Upgrading [PAF m^3.day/MJ_{th}]

No interesting differences appear between the technologies. Each pathway has higher damage potential than the reference system because of the cultivation phases and partly the electricity production.

4.4.10 Terrestrial Ecotoxicity

Chemicals that do not remain long in freshwater and have a high persistence may imply terrestrial or marine effects not yet addressed by USEtox. Therefore, *ReCiPe Midpoint (H) - Terrestrial ecotoxicity* is used, even though ILCD does not recommend any terrestrial ecotoxicity method because none of the existing is complete and exhaustive [32]. ReCiPe characterisation factors allow expressing the emissions in terms of kg 1,4-dichlorobenzene (DB) equivalents. The toxicity according to this method is caused by heavy metals, organic and inorganic emissions to air, to fresh water and to sea water, and heavy metals and inorganic emissions to agricultural and industrial soils.

4.4.10.1 CHP pathways

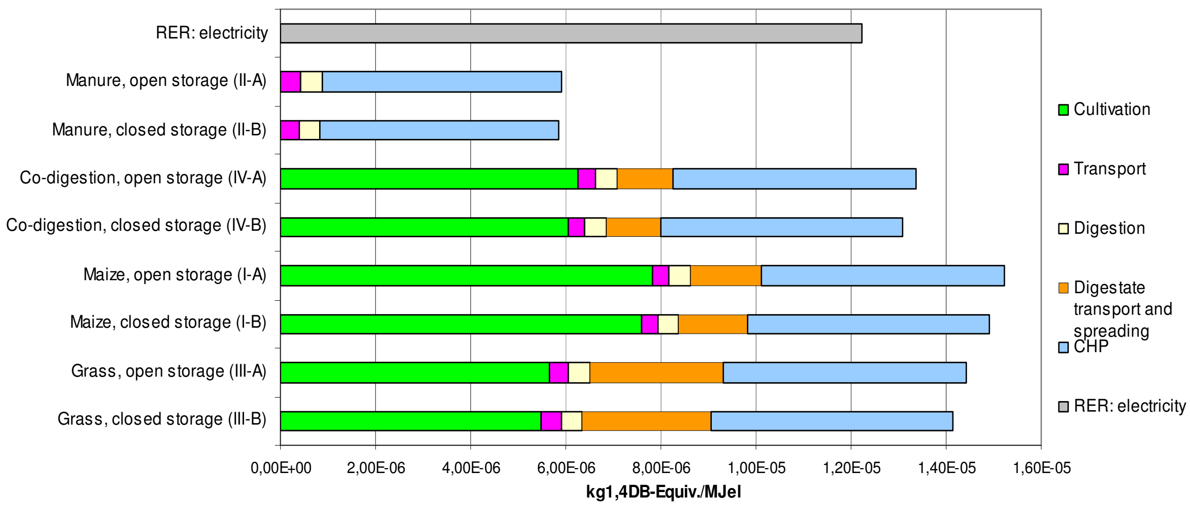


Figure 61 - CHP, Results for terrestrial ecotoxicity [kg1,4DB-Equiv./MJ_{el}], contribution of the processes

- The process that is mainly responsible for this impact is the cultivation, mainly due to phosphorus (more than 80% of the contribution in the cultivation process of both maize and grass). Therefore, the impacts are higher than the reference system if energy crops are digested.
- CHP engine emits formaldehyde that is responsible for about 60% of the impact in this process. Phosphorus linked to the operational diesel used plays the second important role.
- The transport both of digestate and raw material requires diesel that is responsible for phosphorus release in the environment. For this reason, also these processes create

impacts on terrestrial ecotoxicity. The role of digestate transport is more relevant because the mass that has to be transported is more.

- The potential of the reference system is again due to phosphorus linked to refinery products.
- Since digestate transport is not included for manure pathways and no production processes are considered, manure pathways have less potential.

4.4.10.2 Upgrading pathways

- The emissions are very high in maize pathways because of the cultivation, as seen for CHP utilisation.
- Electricity production and upgrading of biogas contribute to create higher effects in pathways without cultivation (manure) or with a low impact biomass production (grass silage). The main responsible is phosphorus.

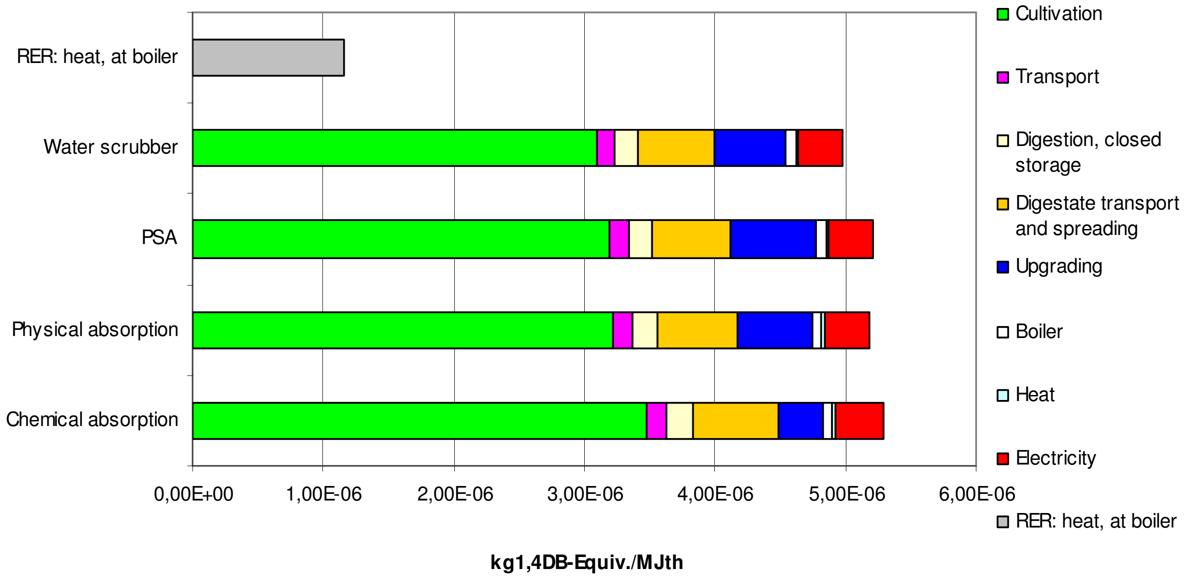


Figure 62 - Upgrading, results for terrestrial ecotoxicity [kg1, 4DB-Equiv./MJ_{th}], contribution of the processes, maize closed storage

	Chemical absorption	Physical absorption	PSA	Water scrubber
Grass, closed storage	326%	319%	321%	301%
Maize, closed storage	356%	347%	349%	328%
Co-digestion, closed storage	301%	296%	298%	279%
Manure, closed storage	11%	27%	33%	22%

Table 47 - Results for terrestrial ecotoxicity, upgrading, increase % of the emissions of the reference system

4.4.11 Abiotic Depletion

The model *CML2001 - Nov. 09, Abiotic Depletion (ADP elements)* accounts for the non renewable material resources and elements consumed during the life cycle. The characterisation factors are named Abiotic Depletion Potentials (ADP) and expressed in kg of antimony (Sb) equivalent, which is the adopted reference element. The abiotic depletion potential is calculated for elements and several mineral compounds. In addition, the method covers most of the substances/materials identified as critical by the European Commission and takes also into account their scarcity [71].

The method does not account for the non renewable energy resources (crude oil, hard coal, lignite, natural gas, uranium).

4.4.11.1 CHP pathways

All the pathways have higher consumption of resources than the reference system.

- For the cultivation phase, for example of grass, the depletion consists mainly of lead and copper consumption (48% of the depletion in cultivation), because of the construction of machinery.
- In CHP process, platinum and copper give the most important contribution (73%).
- During the construction of the digester, chromium and copper are consumed, causing 73% of the depletion in this process.
- The reference system consumes above all copper and chromium (60%), mainly due to the construction of demanding plants such as the nuclear one.

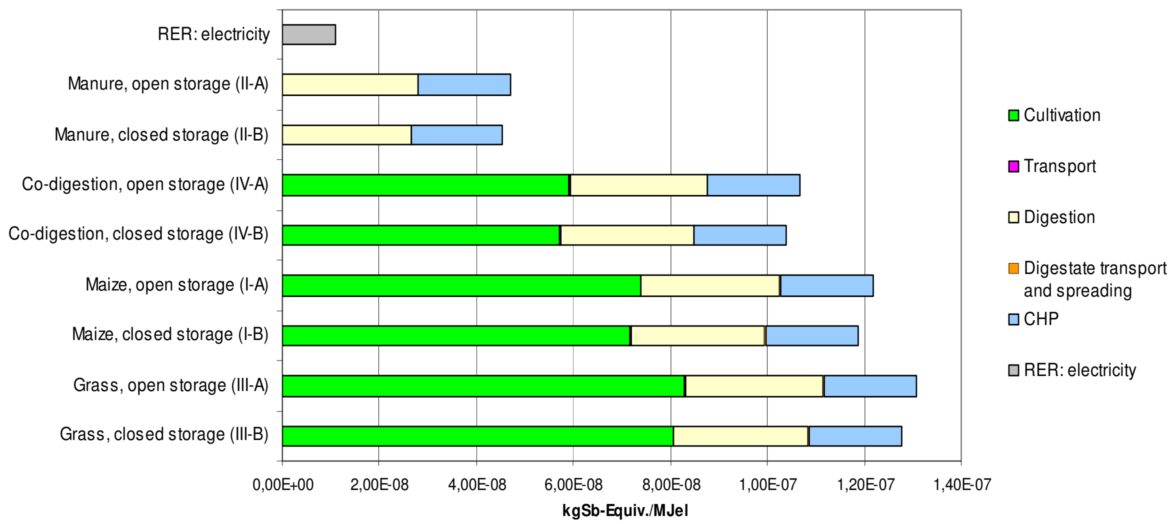


Figure 63 - CHP, Results for freshwater abiotic depletion [kgSb-Equiv./MJ_{el}], contribution of the processes

4.4.11.2 Upgrading pathways

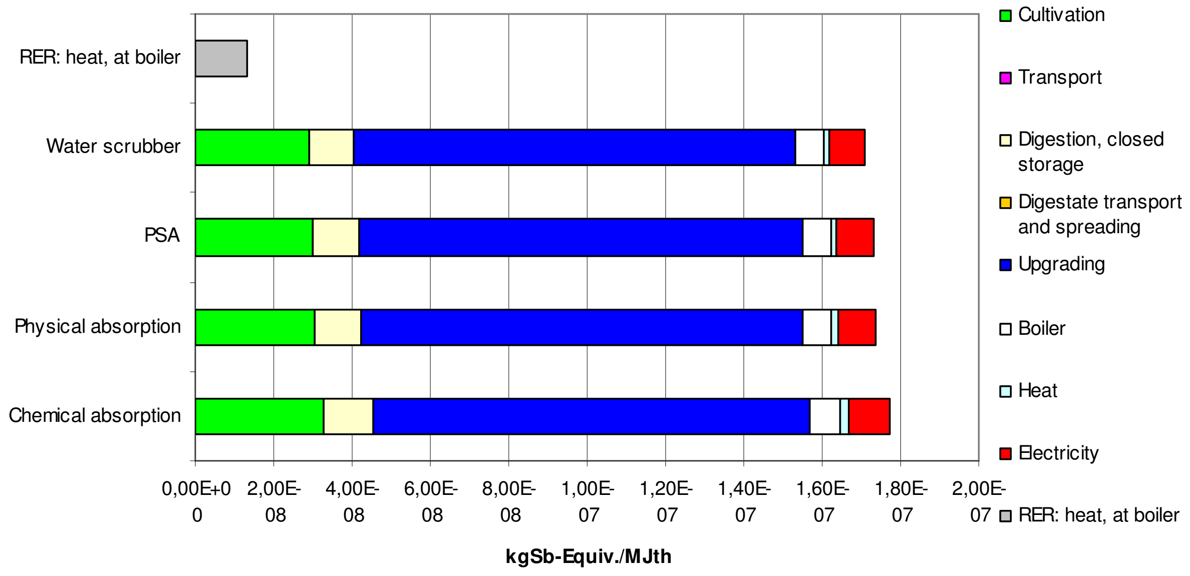


Figure 64 - Upgrading, Results for abiotic depletion [kgSb-Equiv./MJ_{th}], contribution of the processes, maize closed storage

The depletion is higher mainly because of the upgrading phase. The different technologies are not responsible for different consumption: 77% of the depletion in these processes is due to gold and copper, due to the manufacturing of the different upgrading plants that are supposed, for simplicity, to cause the same emissions and to require the same resources in phase of construction.

Also electricity production and heat production with a boiler cause consumption of copper.

Table 48 and Table 49 resume the results. Impacts lower than the reference systems are visualised in green while higher impacts are in red.

CHP	Climate change	Ozone depletion	Human toxicity	Particulate matter	Ionising radiation	Photochem. ozone formation	Acidification	Freshwater Eu-trophication	Marine Eu-trophication	Water Ecotoxicity	Ecotoxicity (terrestrial)	Resource depletion
Grass, closed storage (III-B)	green	green	red	red	green	red	red	green	red	red	red	red
Grass, open storage (III-A)	red	green	red	red	green	red	red	green	red	red	red	red
Maize, closed storage (I-B)	green	green	red	red	green	red	red	green	red	red	red	red
Maize, open storage (I-A)	red	green	red	red	green	red	red	green	red	red	red	red
Co-digestion, closed storage (IV-B)	green	green	red	red	green	red	red	green	red	red	red	red
Co-digestion, open Storage (IV-A)	green	green	red	red	green	red	red	green	red	red	red	red
Manure, closed storage (II-B)	green	green	red	green	green	red	green	green	red	red	green	red
Manure, open storage (II-A)	green	green	red	red	green	red	red	green	red	red	green	red

Table 48 – Review of the results of biogas pathways, CHP. In green, the cases of impact savings

UPGRADING	Climate change	Ozone depletion	Human toxicity	Particulate matter	Ionising radiation	Photochem. ozone formation	Acidification	Freshwater Eu-trophication	Marine Eu-trophication	Water Ecotoxicity	Ecotoxicity (terrestrial)	Resource depletion
Grass, closed storage (III-B)	green	green	red	red	red	red	red	red	red	red	red	red
Maize, closed storage (I-B)	green	green	red	red	red	red	red	red	red	red	red	red
Co-digestion, closed storage (IV-B)	green	green	red	red	red	red	red	red	red	red	red	red
Manure, closed storage (II-B)	green	green	red	green	red	green	green	red	green	red	red	red

Table 49 - Review of the results of biogas pathways, upgrading. In green, the cases of impact savings

4.5 LIFE CYCLE INTERPRETATION: SENSITIVITY ANALYSIS

The consistency check and the completeness check are steps that is useful to follow during all the operations made to model the systems, so in the entire Life Cycle Assessment.
First of all, each step has to be done in order to meet the goal and the scope defined.
Secondly, all the processes have to be analysed to understand whether data collected to model it are appropriate or not.
Finally, the results of the Impact Assessment should clarify if the study can contribute with new information and if the modeling was adequate.
Thus, this work represents only the best results that are possible to obtain with the most suitable data that can be found and calculated considering the time and the means that are established for this project.
Consideration concerning both process modeling and Impact Assessment results are expressed in the previous Paragraphs. In the next section, a sensitivity analysis is proposed to show how the results can be affected by changing values that the completeness check showed to be weakly defined.

4.5.1 Fertilising power of digestate

As said before, in this work it is assumed that digestate is used as fertiliser in agricultural fields, allowing reducing the amount of chemical substances. However, there is little information about the specific content of nutrients in material resulting after digestion of different crops or feedstocks in general.
In this work, an attempt to account for the nutrients with a mass balance is made. However, the results are different from what appears in the scientific literature. Some studies such as Börjesson et al. [13] and Adelt et al. [1] state that digestate can substitute 100% of P and K fertilisers and 60-70% of N fertilisers. It is therefore interesting to analyse if these considerations can affect the results.

The biogas Pathway I-B (Biogas from maize, CHP, closed storage tank) is studied as an example.
Three different scenarios are compared:

- Maize silage is cultivated using chemical fertilisers for 28,05% of P, 12,67% of N and 0% of K, with an additional production of 26,65% of K (Pathway I-B, see Paragraph 4.3.1.7):

- Maize silage is cultivated with 100% chemical fertilisers (as assumed in Ecoinvent 2.2)
- Maize silage is cultivated without P and K chemical fertilisers and using chemical fertilisers to provide 40% of the N required (40% of N fertiliser required according to Ecoinvent 2.2).

Results in Table 50 show that the employment of chemical fertilisers as modelled in Ecoinvent 2.2 causes higher or the same impacts than considering digestate utilisation. However, the lowest emissions due to avoided chemical production are never enough to change significantly the sustainability of the pathway. Also the benefits in considering different percentages of fertilisers used are not significant for many impacts.

The different percentages of chemical fertilisers used do not affect significantly the results. This is due to the fact that what changes in the scenarios analysed is only the production of the fertilisers, but the emissions to air, water and soil of the employment of both fertilisers and digestate during the growth of the plant is considered the same because of the lack of information. Other studies are required, both in literature and in the field. This will lead to the necessity to better understand the nutrients recirculation, since this uncertainty could affect the results.

	100% chemical fertilisers	**% fertilisers in literature**	**This study**	**Reference system**	**Unit/MJ$_{el}$**
Climate change	0,0929	0,0879	0,0895	0,1352	kg CO_2-Equiv.
Ozone depletion	6,31E-09	5,92E-09	6,15E-09	6,42E-09	kg R11-Equiv.
Human toxicity	2,82E-10	2,82E-10	2,82E-10	1,04E-12	Cases
Particulate matter	3,52E-04	3,46E-04	3,51E-04	9,9E-05	kg PM2.5-Eq.
Ionising radiation	1668,44	1465,96	1587,20	35523,39	kg U_{235} eq
Photochemical ozone formation	0,0020	0,0020	0,0020	0,0003	kg NMVOC
Acidification	0,0019	0,0018	0,0019	0,0006	kg SO_2-Equiv.
Eutrophication (freshwater)	1,59E-05	1,43E-05	1,48E-05	1,15E-04	kg P eq
Eutrophication (marine)	1,51E-03	1,51E-03	1,51E-03	1,13E-04	kg N eq
Ecotoxicity (freshwater)	0,0508	0,0508	0,0508	7,18E-05	PAF m^3.day
Ecotoxicity (terrestrial)	1,49E-05	1,50E-05	1,48E-05	1,22E-05	kg 1,4DB eq
Resource depletion	1,19E-07	1,39E-07	1,11E-07	1,10E-08	kg Sb-Equiv.

Table 50 – Results of the sensitivity analysis on fertilising power of digestate

4.5.2 Grass as residue

Since the cultivation phase is the main responsible for the higher GHG emission in grass pathways, it is interesting to realise how the situation could change if the production processes are not taken into account. This can be a right approach if grass is not cultivated within the agricultural sector (for crop rotation, fodder or energy purposes). In fact, the availability of grass is anyhow relevant because it can spontaneously grow on set-aside lands.

The biogas Pathway III-B (Biogas from grass, CHP, closed storage tank) is studied as an example.

Three different scenarios are compared:

- Grass silage is cultivated (Pathway III-B)
- Grass silage is not cultivated (Pathway III-B in which the boundaries includes only the transport phase)
- Maize silage is cultivated (Pathway I-B)

	Grass silage without cultivation	Grass silage with cultivation	Maize silage (with cultivation)	Reference system	Unit/MJ_{el}
Climate change	0,0565	0,1161	0,0895	0,1352	kg CO_2-Equiv.
Ozone depletion	3,73E-09	6,21E-09	6,15E-09	6,42E-09	kg R11-Equiv.
Human toxicity	2,81E-10	2,81E-10	2,82E-10	1,04E-12	Cases
Particulate matter	2,78E-04	5,38E-04	3,51E-04	9,9E-05	kg PM2.5-Eq.
Ionising radiation	635,54	1615,05	1587,20	35523,39	kg U_{235} eq
Photochemical ozone formation	0,0019	0,0021	0,0020	0,0003	kg NMVOC
Acidification	0,0015	0,0041	0,0019	0,0006	kg SO_2-Equiv.
Eutrophication (freshwater)	3,61E-06	1,77E-05	1,48E-05	1,15E-04	kg P eq
Eutrophication (marine)	7,07E-04	1,14E-03	1,51E-03	1,13E-04	kg N eq
Ecotoxicity (freshwater)	0,0003	0,0008	0,0508	7,18E-05	PAF m^3.day
Ecotoxicity (terrestrial)	8,66E-06	1,42E-05	1,49E-05	1,22E-05	kg 1,4DB eq
Resource depletion	4,71E-08	1,28E-07	1,19E-07	1,10E-08	kg Sb-Equiv.

Table 51 - Results of the sensitivity analysis on grass cultivation

The analysis is an evidence for the fact that the use of residual grass to produce biogas can have several benefits and be a better solution than the digestion of other energy crops especially cultivated.

Even though the positive or negative values of each impact category remain the same compared to the reference systems, if cultivation is neglected the equivalent emissions and resources consumption have very lower values than the scenario with the production inside the boundaries. For example, the high potential on resource depletion and acidification decrease (the values approach the reference system) while for climate change and ozone depletion the impacts decline once more and the savings increase.

Only according to terrestrial ecotoxicity, if the employment of fertilisers and machinery is avoided the impact becomes positive.

Moreover with these values grass silage becomes more environmentally convenient than maize silage, for which discounting the crop growing does not make sense.

4.5.3 Manure with and without credits

In this analysis, it is shown how considering or not the avoided emissions of undigested manure can affect the results.

For CHP utilisation, both open (II-A) and closed storage tank (II-B) are used to compare the results considering or not the benefits of the change in manure management.

For the cases with upgrading, only the pathway VI-B (CHEM) (chemical absorption and closed storage tank) is used as an example.

Generally the impacts are higher for the open storage of digestate than the closed and when the alternative fate of undigested manure is not considered than when credits are accounted for.

However, only in the following case a significant variation in considering credits is demonstrated to occur:

- **Climate change**: open storage without credits results in higher greenhouse gases emissions than the reference system. This means that CH_4 and N_2O coming from the storage tank of the digestate are relevant. The emissions due to undigested manure are able to mitigate this potential.
- **Particulate matter**: the pathway is sustainable considering credits and closing the storage tank only. Avoiding credits account leads to attribute ammonia emissions that are responsible for particulate matter potential formation.
- **Acidification**: the trend is similar to particulate matter formation. The main responsible is again NH_4. In this case, credits consent to have about 380% less kgSO_2-Equiv. in case of open storage and higher savings for closed storage.

Concerning upgrading, the account of credits is responsible for better situations concerning **particulate matter, photochemical ozone formation, acidification and marine eutrophication,** as seen in Table 53.

As a result, it should be always recommended to consider credits (or to account for the emissions of undigested manure in the reference system) because it results correctly in lower impacts.

CHP	Closed storage (II-B)		Open storage (II-A)			
	No credits	Credits	No credits	Credits	Reference system	Unit/MJ_{el}
Climate change	0,0561	-0,3554	0,2422	-0,1911	0,1352	kg CO^2-Equiv.
Ozone depletion	4,17E-09	3,64E-09	4,22E-09	3,66E-09	6,42E-09	kg R11-Equiv.
Human toxicity	2,76E-10	2,76E-10	2,77E-10	2,77E-10	1,04E-12	Cases
Particulate matter	4,83E-04	7,33E-05	6,85E-04	2,54E-04	9,90E-05	kg PM2.5-Eq.
Ionising radiation	838,61	590,79	866,85	605,90	35523,39	kg U_{235} eq
Photochemical Ozone formation	0,0018	0,0016	0,0018	0,0017	0,0003	kg NMVOC
Acidification	0,0042	-0,0002	0,0058	0,0012	0,0006	kg SO^2-Equiv.
Eutrophication (freshwater)	4,39E-06	3,49E-06	4,53E-06	3,58E-06	1,15E-04	kg P eq
Eutrophication (marine)	8,37E-04	5,66E-04	9,37E-04	6,51E-04	1,13E-04	kg N eq
Ecotoxicity (freshwater)	0,0003	0,0003	0,0003	0,0003	0,0001	PAF m^3.day
Ecotoxicity (terrestrial)	6,55E-06	5,86E-06	6,64E-06	5,91E-06	1,22E-05	kg 1,4DB eq
Resource depletion	6,66E-08	4,54E-08	6,92E-08	4,69E-08	1,10E-08	kg Sb-Equiv.

Table 52 - Results of the sensitivity analysis on manure with or without credits, CHP

Upgrading, chemical absorption	No credits	Credits	Reference system	Unit/MJ_{th}
Climate change	0,0283	-0,1624	0,0772	kg CO_2-Equiv.
Ozone depletion	9,92E-10	7,45E-10	1,19E-08	kg R11-Equiv.
Human toxicity	5,12E-12	5,10E-12	4,80E-12	cases
Particulate matter	1,41E-04	-4,89E-05	1,06E-05	kg PM2.5-Eq.
Ionising radiation	2938,96	2824,12	431,06	kg U_{235} eq
Photochemical ozone formation	9,74E-05	1,39E-05	5,9E-05	kg NMVOC
Acidification	0,0016	-0,0004	0,0001	kg SO_2-Equiv.
Eutrophication (freshwater)	1,29E-05	1,25E-05	2,04E-06	kg P eq
Eutrophication (marine)	1,18E-04	-7,63E-06	1,78E-05	kg N eq
Ecotoxicity (freshwater)	9,28E-05	8,27E-05	2,08E-05	PAF m^3.day
Ecotoxicity (terrestrial)	1,61E-06	1,29E-06	1,16E-06	kg 1,4DB eq
Resource depletion	1,52E-07	1,42E-07	1,32E-08	kg Sb-Equiv.

Table 53 - Results of the sensitivity analysis on manure with or without credits, upgrading (chemical absorption)

4.5.4 Emissions of N_2O from digested and undigested manure

Considering its high Global Warming Potential, it is essential to evaluate carefully the emissions of nitrous oxide that occurs in the entire life cycle of biogas production and utilisation. As said before, the emissions from raw and digested manure are taken from Amon et al [5 and 4] but in literature there is lack of certain information and not comparable values are found. In addition, in literature no data represent the emissions that originate from different kind of residues of the digestion of feedstocks such as the energy crops. In this study, assumption and correction allowed to use in any case the data of digested manure. It is therefore interesting to understand how the sustainability of climate change impact category can significantly change according to N_2O emissions attributed to the feedstock and to the digestate.

The results on the impacts on **climate change** are reported hereafter:

- N_2O emissions in the open storage of digestate, CHP: Figure 65 represents the situation with different percentage of N_2O emitted from the digestate in the open storage tank, where 100% corresponds to the values calculated with Amon et al [5, 4]. X axis is the reference system. Manure and co-digestion pathways maintain a lower kgCO_2-Equiv. than the reference system unless N_2O is three times higher than the baseline scenario. Maize pathway can be better than the reference system if the real N_2O emissions are lower than 50% of the value considered in this study, while grass silage pathway is not sustainable from this point of view even if nitrous oxide in the storage is posed equal to zero.

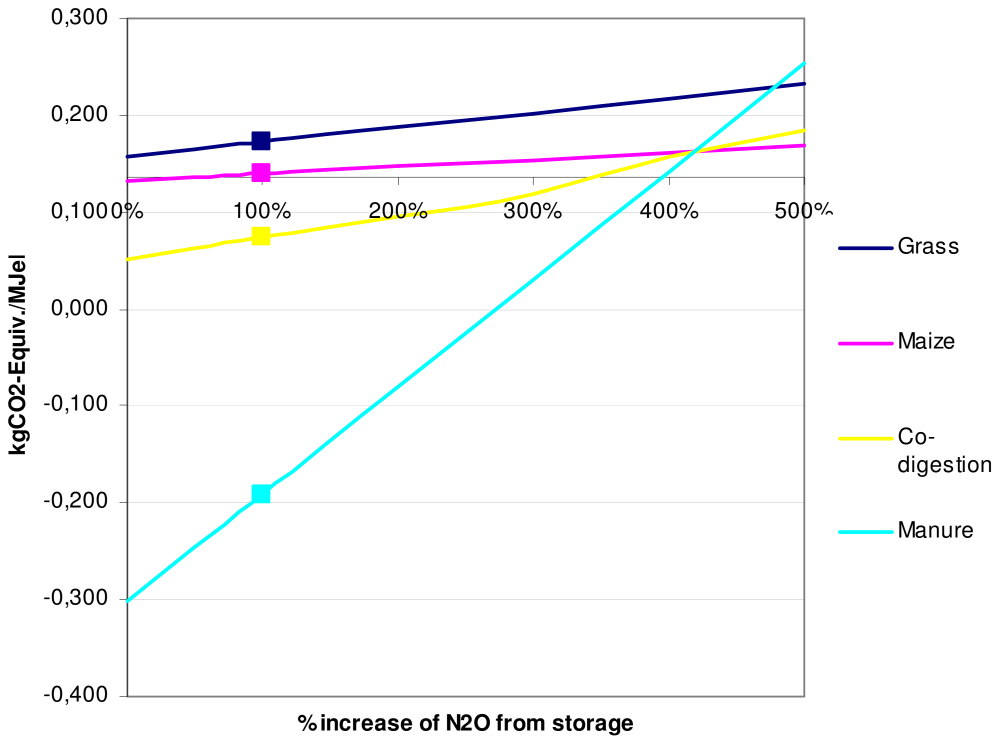


Figure 65 – GWP 100 with different percentages of N_2O emitted during the storage of the digestate, CHP

- N_2O emissions in the open storage of digestate, upgrading: in the example, the case of maize digestion is represented. Attention must be paid in case of water scrubbing, while chemical absorption tolerates higher emissions.

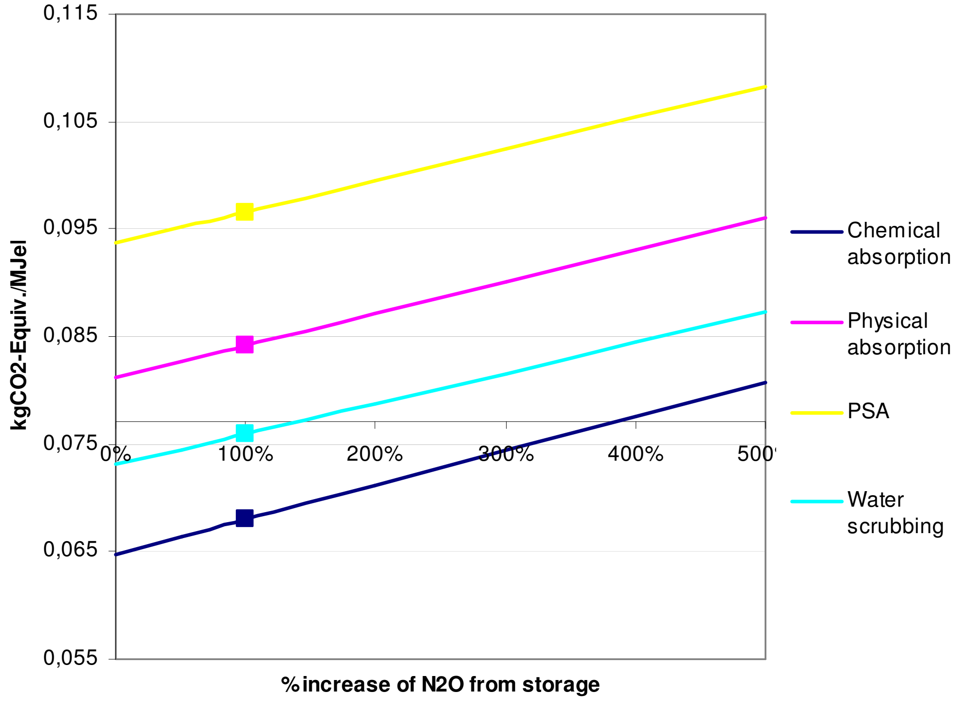


Figure 66 – GWP 100 with different percentages of N_2O emitted during the storage of the digestate, upgrading

- N_2O emissions in spreading the digestate, CHP: only very elevated values of N_2O emissions could have interesting impact on the sustainability of the pathways. The same happens in case of upgrading.

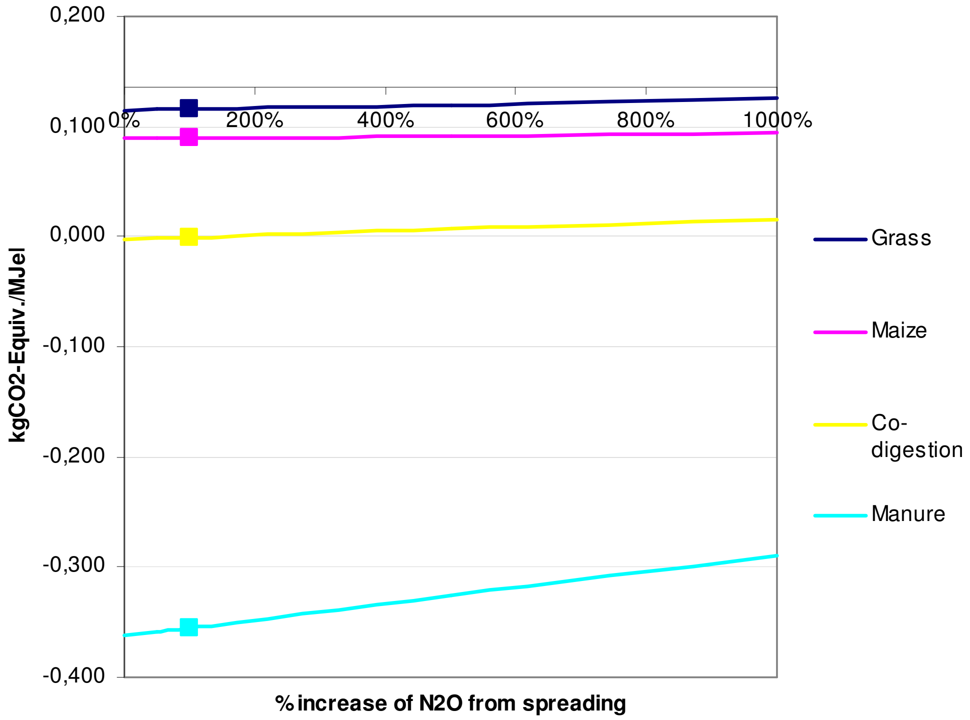


Figure 67 – GWP 100 with different percentages of N_2O emitted during the spreading of the digestate, CHP

- N_2O credits for manure pathways: even if nitrous oxide credits are considered zero, thanks to methane credits the emissions are far below the reference system.

4.5.5 Methane leakages from upgrading plants

The upgrading phase is responsible for methane leakages in the atmosphere in relation with the efficiency in removing undesired compounds of each method. Different efficiencies can be found in real plant since the values considered before as found in literature are mainly the best results that are guaranteed by constructors.
The ranges of different percentage of leakages that can be found in real plants are taken from the study of Holmgren [41] (see Paragraph 4.5.3.5). Also the range of emissions found in literature and resumed in Table 20 is considered. The pathway analysed is the upgrading of maize with closed storage tank of the digestate.

Since methane leakages mainly influence the **climate change**, only this impact category is analysed, with the method CML2001 - Nov. 09, Global Warming Potential (GWP 100 years) [kg CO_2-Equiv.].

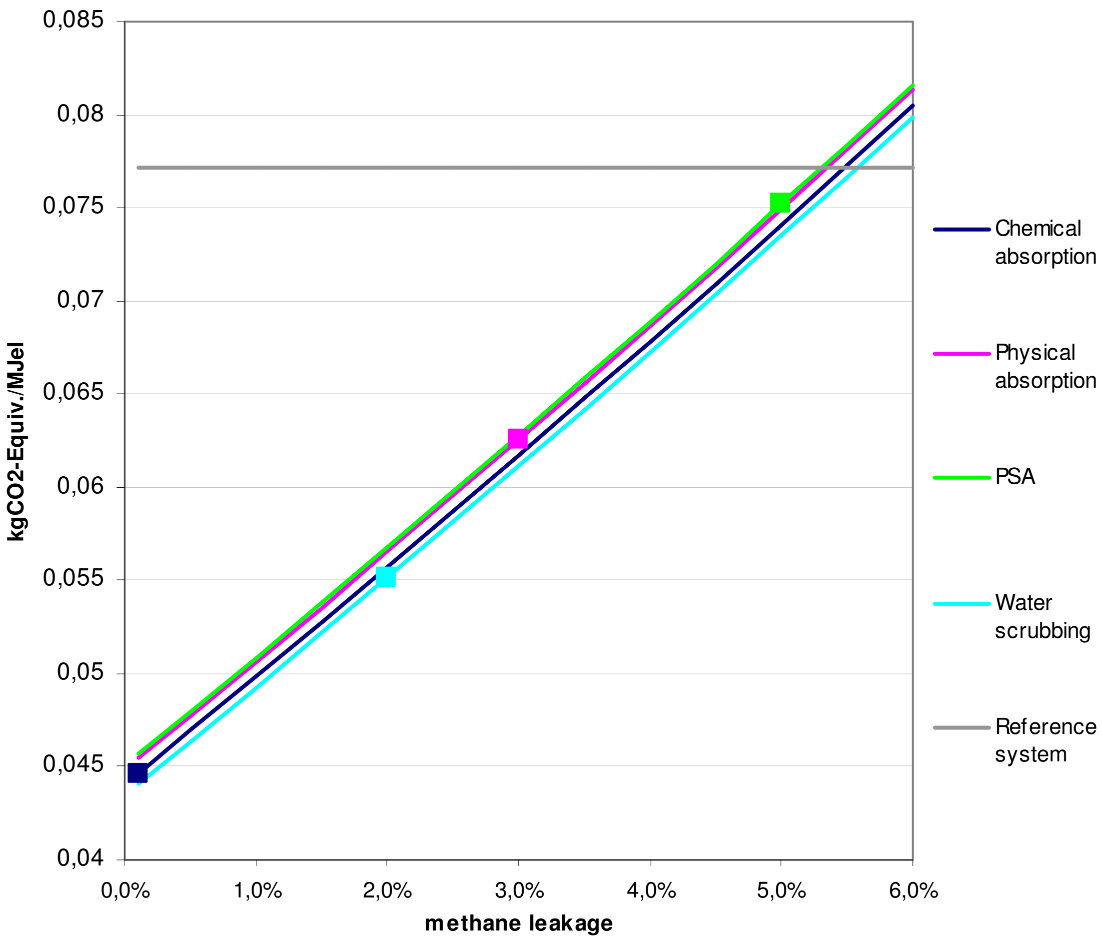


Figure 68 – Impact on climate change of upgrading technologies with different % of methane leakages

The trend is the same for each technology. It is clear that a maximum leakage of 5,5% is allowed to remain in a sustainable situation in the current impact category.

- Chemical scrubbing assures low GHG emissions with a certain confidence, because both Holmgren [41] and the references in literature agree that leakages are around 0,1%. It makes this technology the most favourable for greenhouse gas savings.
- Physical absorption is not analysed in Voluntary Agreement, but in literature the range [2%, 4%] guarantees that the emissions remains below the reference system.
- PSA is supposed to have methane leakages variable from 1 to 10% (see Table 20), even though in real plants CH_4 emissions seem to be far lower (underneath 2,5%) and under the critical threshold of 5,5% (see Figure 11).
- On the contrary, although in literature water scrubbing is responsible for 1%-2% of CH_4 leakages, Swedish real plants participating to Voluntary Agreement show that the range of uncertainty can be extended from 0,1% to 6%. Therefore, attention must be paid to assure that leakages do not rise above 5,5%.

In conclusion, according to global warming potential the safest technology remains chemical absorption, followed by physical absorption. Water scrubbing is an interesting alternative if methane leakage reflects the value found in literature, while PSA emissions as measured in real plants should be guarantee to remain inside the sustainability boundaries.

4.5.6 Flaring of the off-gas in upgrading plants

Since the residual stream of the upgrading phase is a biomethane-rich gas, it should be combusted in order to convert its carbon content in carbon dioxide that is biogenic and therefore does not accounts for GHG potential. An additional process is created on the basis on Ecoinvent 2.2 “RER: natural gas, sour, burned in production flare”. The waste stream, that contains a different percentage of methane depending on the upgrading technology considered, is supposed to be flared with 99,9% of efficiency. No carbon dioxide is accounted for, while sulphur dioxide is calculated with a stoichiometrical conversion considering the maximum H_2S admitted with biomethane. The values of the other by-products of the combustion found in Ecoinvent process are assumed.
The analysis is performed considering biogas production from maize with closed storage tank of digestate.

The sustainability of the pathway concerning the various impact categories never changes in burning the off-gas. This is mainly due to the cultivation phase that often represents the main source of potential impacts. However, considerable differences are found for these impacts:

- **Climate change**: flaring the off-gas results in lower GHG emissions that make the four technologies having slight differences. The benefits are higher for the techniques that have more methane leakages.

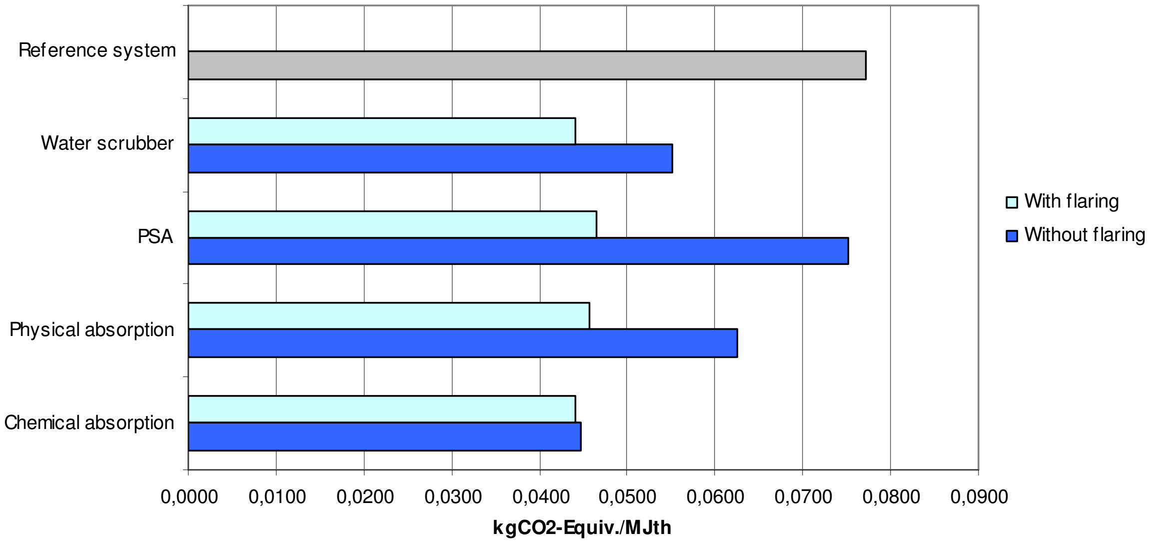


Figure 69 - Upgrading, maize closed storage with and without flaring the off-gas, results for climate change

- **Particulate matter formation**: since the combustion is responsible for an additional release of dust, sulphur dioxide and nitrogen oxides, the additional process causes a higher impact. This contribution reflects the efficiency of the capture of the biomethane by the upgrading technology.

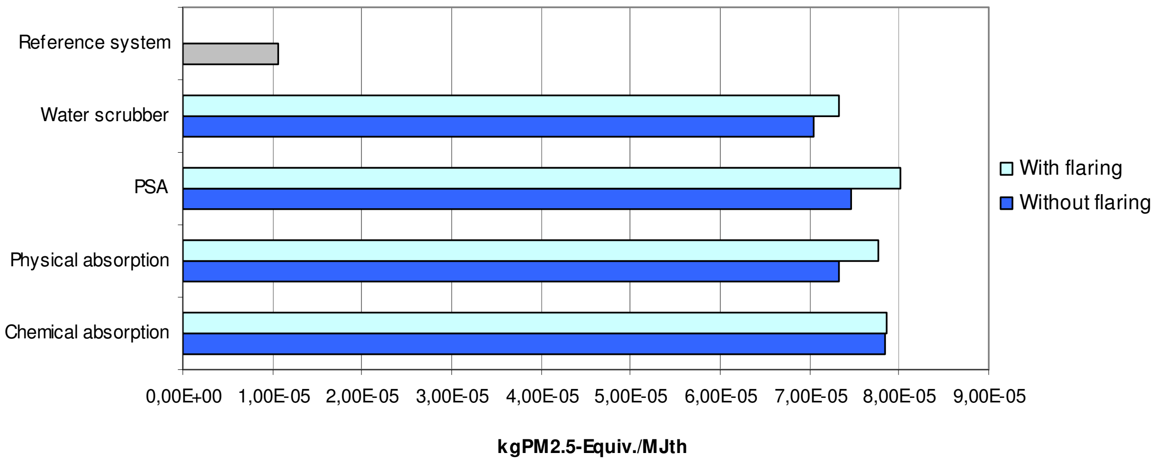


Figure 70 - Upgrading, maize closed storage with and without flaring the off-gas, results for PM formation

- **Photochemical ozone formation** and **marine eutrophication**: the trend reflects the situation in Figure 70. It is mainly due to nitrogen oxides.

- **Acidification**: again, chemical absorption does not show benefits in flaring and during the life cycle the most elevated amount of kgSO_2-Equiv. are released. Concerning the other technologies, higher impacts of flaring scenarios are due to nitrogen oxides and sulphur dioxide.

In conclusion, flaring the off-gas is an efficient technique for water scrubbing because it helps to have the same GHG emissions as chemical absorption that is the most efficient in terms of methane leakages. In addition, the further emissions caused by the combustion of the biogas residue are still lower than other technologies.
For chemical absorption, the combustion of residues is worthless.
PSA and chemical absorption can be competitive because they can reach large GHG savings, but increasing the potential to create other impacts.

4.5.7 Producing heat and electricity inside the plant in case of upgrading

Usually, in plant equipped for biomethane production the electricity required for plant operation is provided by the public grid and there is no electricity generation unit on site [1]. Heat is generated instead in a boiler that burns biogas, as shown in Paragraph 4.2.9.2 and 4.2.10.2.
Actually some impact categories result negative because of the employment of the electricity from the European mix. The aim of this sensitivity analysis is to show whether the results could turn into positive by producing energy with the biogas itself. This implies that the plant should be equipped with a CHP engine that produces both the heat and electricity required.

In this example, chemical absorption is chosen as representative. Each feedstock is evaluated in case of closed storage tank. The CHP device that is supposed to be used is the typical biogas engine defined in Paragraph 4.2.6. It is also assumed that the main purpose of its installation is the providing of all the thermal energy needed. The efficiency of the engine, in combination with the requirement of electricity that is lower than the heat one, implies that additional energy is produced and sold to the grid, avoiding the utilisation of traditional fuels. This production is calculated to be about 0,1 MJ of electricity.
In Table 54, colours indicate if the scenario is better (green) or worse (red) than the reference system. Hereafter the effects found are detailed.

- **Climate change:** GHG savings are higher in each scenario.
- **Abiotic depletion**: each feedstock causes low resources consumption, but the reference system is still better. The same occurs to **human toxicity**.
- **Ionising radiation**, **freshwater eutrophication and ozone depletion**: emissions are negative because of the supplementary production of electricity that avoids the traditional production including fossil fuels.

- **Acidification**, **particulate matter formation** and **terrestrial ecotoxicity:** the amounts released are fewer, but only in manure digestion are beneath the reference system. The sustainability reflects the baseline scenario.
- **Photochemical ozone formation**, **freshwater ecotoxicity** and **marine eutrophication:** CHP introduction increases the harmful effects mainly because more biomass has to be digested in order to provide the additional amount of biogas to produce energy. Therefore, further emissions linked to cultivation, digestion, transport of the raw material and the digestate are the major responsible for the higher total amount.

	Grass	Maize	Manure	Co-digestion	Reference system	Unit/MJ_{th}
Climate change	0,006323	-0,00739	-0,24144	-0,05436	0,077161	kg CO2-Equiv.
Ozone depletion	-3,29E-10	-3,65E-10	-1,80E-09	-6,48E-10	1,19E-08	kg R11-Equiv.
Human toxicity	4,26E-11	4,27E-11	4,16E-11	4,25E-11	4,8E-12	Cases
Particulate matter	0,000167	7,01E-05	-7,4E-05	4,12E-05	1,06E-05	kg PM2.5-Eq.
Ionising radiation	-12149,7	-12183,5	-13628,6	-12440,2	431,055	kg U235 eq
Photochemical Ozone formation	0,000337	0,000299	0,000115	0,000262	5,91E-05	kg NMVOC
Acidification	0,001587	0,000436	-0,00065	0,000217	6,65E-05	kg SO2-Equiv.
Eutrophication (freshwater)	-3,68E-05	-3,83E-05	-4,75E-05	-4,00E-05	2,04E-06	kg P eq
Eutrophication (marine)	0,000313	0,000506	1,9E-05	0,000408	1,78E-05	kg N eq
Ecotoxicity (freshwater)	0,000307	0,025995	7,59E-05	0,020779	2,08E-05	PAF m3.day
Ecotoxicity (terrestrial)	2,89E-06	3,28E-06	-1,53E-06	2,32E-06	1,16E-06	kg DCB-Equiv.
Resource depletion	1,63E-07	1,58E-07	1,20E-07	1,51E-07	1,32E-08	kg Sb-Equiv.

Table 54 - Results of the sensitivity analysis on manure with or without credits, upgrading (chemical absorption)

In conclusion, interesting benefits can be found concerning for example GHG savings, ionising radiation and freshwater eutrophication. On the contrary, CHP introduction implies a lower yield of biomethane production of all the chain, meaning that some higher impacts occur because of the additional effort in the management raw and digested material.

5

COMPARISONS BETWEEN THE LCA AND THE RENEWABLE ENERGY DIRECTIVE

"This Directive establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy and for the share of energy from renewable sources in transport. It lays down rules relating to statistical transfers between Member States, joint projects between Member States and with third countries, guarantees of origin, administrative procedures, information and training, and access to the electricity grid for energy from renewable sources. It establishes sustainability criteria for biofuels and bioliquids."

Directive 2009/28/EC [34]

In 2020, at least a 20% share in the Community's consumption of energy shall come from renewable sources. For this purpose the Renewable Energy Directive (2009/28/EC) (RED) establishes a common framework for the promotion of energy from renewable sources. It sets mandatory national targets of how much each Member State will have to contribute to the 20%- target (Annex I), and it defines an extra target for the transport sector of 10% from renewable sources, being the same for each Member State (Article 3 (4)).
As this target will be covered mainly by biofuels, the RED sets sustainability criteria for biofuels and bioliquids. These criteria refer to the protection of land with high ecological value, greenhouse gas emission savings, and the socio-economic impact [34].

Biofuels which shall be accounted for towards the national targets need to comply with a number of sustainability criteria (Article 17).
The minimum greenhouse gas emission saving from the use of biofuels must be 35%. From 2017, it must be 50%, and from 2018 it must be 60% for new installations.
Raw materials for biofuels must not come from land that had one of the following statuses in 2008 and no longer has that status: primary forest, protected area, highly biodiverse grassland, areas with high stocks of carbon, or peatlands.
For social and economical sustainability, the RED does not set any must-criteria. However, it requests, every two years, a report of the European Commission on the impact of EU's biofuel policy.
The Member States shall require economic operators to show the compliance with the sustainability criteria (Article 18). Economic operators therefore have to use a mass balance system which allows consignments of raw material or biofuel with differing sustainability characteristics to be mixed, and they have to arrange for an adequate standard of independent auditing of the information.
Regarding imports of raw material or biofuels, the EU shall seek to make bilateral or multilateral agreements with third countries that guarantee compliance with the sustainability criteria.
RED Annex V give default values of 22 biofuel production pathways that may be used (Article 19). For other production pathways economic operators have to do their own calculations according to the methodology in the same Annex. In doing so disaggregated default values may be used for some factors (e.g. for the transportation of biofuels). Total GHG emissions are the sum of emissions from cultivation, processing and transportation of biofuels.
Default values are only valid if no land use change has taken place for cultivation of the raw materials, and when raw materials are cultivated:
- outside the EU, or
- in the EU in areas included in one of the lists provided by Member States in 2010. [34]

In February 2010, as required by article 17 of the RED, the Report from the Commission to the Council and the European Parliament on sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling (COM(2010) 11) [29] was published, accompanied by an Impact Assessment (SEC(2010) 65) [30]. These documents stated that the introduction of sustainability criteria for solid and gaseous biomass was unnecessary, but the Commission recommended Member States to set national criteria using the same approach as for biofuels and bioliquids, as estabilished by the RED [29].
A second report should have been published by the end of 2011 which would have assessed the impacts of national sustainability rules on bioenergy development, but the Commission is still working on it.

Solid and gaseous biomass are defined as the one originated from agricultural crops and residues (e.g. maize, wheat, straw, animal manure), from forestry (e.g. logs, stumps, leaves and branches), wood processing industries (bark, off-cuts, wood chips, sawdust) and from organic waste (e.g. municipal solid waste, post consumer recovered wood, refuse-derived fuels, sewage sludge) [29]. For that reason, biogas that originates from digestion of energy crops and animal slurries is considered a gaseous biomass.

The application of RED criteria to solid and gaseous biomass presents a number of both benefits and complications. It seems the most logical option in view of having uniform requirements for different supply chains.
However, practical difficulties come up when dealing with the fossil fuel comparator, since SEC(2010) suggest that the sustainable character of these biomass will depend on the efficiency of power plants, meaning that the same biogas might be sustainable used as vehicle fuel for example but not in a stationary engine.
In addition, the question whether a feedstock constitutes a residue or not is crucial as residues are exempt from LUC and production emissions. There is a need to have a clear definition or list of residues which needs to be certified and verifiable [23].

Except for the need to protect areas with high biodiversity value, with high-carbon stock or undrained peatland, it is set that environmental sustainability is linked only to the greenhouse gas emissions. Therefore, all the other positive or negative impacts that emerge considering the detailed life cycle of the gaseous fuel with a LCA approach are neglected. In addition, the methodology does not account for:
- machinery production;
- credits due to the alternative fate of the biomass (credits).

5.1 RED ANNEX V METHODOLOGY

The methodology for calculating GHG performance of solid and gaseous biomass used in electricity, heat and cooling is the following [29]:

E = total emissions from the production of the fuel before energy conversion;

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$$

where

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualised emissions from carbon stock changes caused by land use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

e_u = emissions from the fuel in use, that represents the greenhouse gases emitted during the combustion of solid and gaseous biomass; this value shall be taken to be zero;

e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;

e_{ccs} = emission savings from carbon capture and geological storage, and;

e_{ccr} = emission savings from carbon capture and replacement.

Emissions from the manufacture of machinery and equipment shall not be taken into account.

The greenhouse gases taken into account shall be CO_2, N_2O and CH_4. For the purpose of calculating CO_2 equivalence, those gases shall be valued as follows: CO_2 = 1, N_2O = 296, CH_4 = 23

Greenhouse gas emissions from the use of solid and gaseous biomass in producing electricity, heating or cooling (*EC*) shall be calculated by dividing E by the efficiency of electricity or heat or cool. These emissions shall be expressed in terms of grams of CO_2 equivalent per MJ of final energy commodity (heat, cooling or electricity), gCO_2eq/MJ.

Greenhouse gas emission savings from heat, cooling and electricity being generated from solid and gaseous biomass shall be calculated as: $(EC - EC_F)/EC_F$

- For solid and gaseous biomass, for electricity production, the fossil fuel comparator $EC_{F(el)}$ shall be 198 $gCO_2eq/MJ_{electricity}$.
- For solid and gaseous biomass used for heating production, the fossil fuel comparator $EC_{F(h)}$ shall be 87 gCO_2eq/MJ_{heat}.

5.2 DIFFERENCES BETWEEN RES AND LCA APPROACH

The Commission analysed some pathways concerning biogas production, providing typical and default GHG emissions values [gCO_2eq/MJ_{fuel}] divided into the phases of cultivation (e_{ec}), processing (e_p) and transport-distribution (e_{td}), that can be used the biomass is produced with no net carbon emissions from land use change (Annex II).

Typical value means an estimate of the representative greenhouse gas emission saving for a particular biofuel production pathway*; default value* means a value derived from a typical value by the application of pre-determined factors (usually 1,2) and that may, in circumstances specified in the Directive, be used in place of an actual value [34]. The results are reported in Table 55.

5.2.1 Greenhouse gases

To calculate the emissions in terms of gCO_2-Equiv, the impact method recommended and chosen in this LCA (CML2001 - Nov. 09, Global Warming Potential (GWP 100 years)) considers all the gases with a Global Warming Potential, as developed by the Intergovernmental Panel on Climate Change (IPCC) in the Fourth Assessment Report (AR4, 2007) [32].

In this updated report, IPCC attributes the following GWP_{100} [44]:

CO_2 = 1

CH_4 = 25

N_2O = 298

The values are higher than the equivalence values considered in RED, leading to lower GHG emissions calculated with this last approach.

In addition, IPCC considers many other compounds grouped in the following categories: Substances controlled by the Montreal Protocol (mainly CFC, HCFC and Halon), Hydrofluorocarbons, Perfluorinated compounds, Fluorinated ethers, Hydrocarbons [44].

5.2.2 The efficiency

The energy conversion efficiency is an important assumption that is necessary in order to compare the emissions of the fuel with the comparator since the default/typical values refer only to biogas production.

Concerning biogas utilisation in CHP devices to obtain 1 MJ of electricity, it is necessary to set the efficiency of electricity production for example to 36%, from which it is necessary to subtract the internal consumption of the plant.

As far as biomethane production and utilisation is concerned, the efficiency of heat recovered after its combustion in a small boiler can be assumed around 85%, but all the leakages and the emissions that occur during the upgrading and the injection into the gas grid are not considered.

All these problems result in overestimating the GHG performance of biogas pathways.

The results concerning default and typical values divided by the efficiency factor are showed in Table 56. In the following paragraphs, the comparisons are made considering the default values because they are more conservative.

5.2.3 Biogas from maize

Two pathways were analysed, considering a traditional cultivation or an organic farming (without the utilisation of chemical fertilisers and pesticides). This difference only affects the emissions in the production process.

5.2.3.1 CHP Pathways

- Cultivation: default values are higher than the emissions calculated in this LCA. The yield of biogas production of the feedstock considered in this study is higher, then less maize is required and the cultivation results in less GHG emissions.
- Processing: if the typical values are compared with the results of a closed storage tank, the emissions in RED methodology are higher because of the reasons showed for cultivation, even considering the spreading of the digestate. Concerning the open storage tank, higher emissions characterise the LCA since the important emissions from the storage are accounted for.
- Transport: in default values this phase is negligible, while LCA results in about 1,6 gCO_2-Equiv.
- Other processes: the emissions linked to the utilisation of the biogas produced are not considered in the RES methodology, since the efficiency factor applied to default value considers only the efficiency of the electricity recovered. With LCA approach, 31 gCO_2 – Equiv. are calculated to be emitted because of GHG leakages and the construction of the plant.

5.2.3.2 Upgrading Pathways

- Cultivation: default values are little higher than the emissions calculated in this LCA for the closed storage. LCA shows different GHG results according to the upgrading technology chosen. Chemical absorption gives the highest emissions.
- Processing: the emissions are comparable between the two methods, since the processing is linked to the feedstock in cultivation. Again, chemical absorption is the highest-influencing upgrading technology.
- Transport: RED methodology considers this phase negligible, while LCA results in 0,7 gCO_2-Equiv.
- Other processes: the upgrading of the biogas, the injection into the gas grid and the utilisation in a boiler are responsible for GHG emissions linked to heat and electricity production, equipment and reagents manufacturing, leakages. For this reason, LCA calculated additionally GHG emissions that are very different according to the upgrading method chosen. Chemical absorption emits 17,6 gCO_2-Equiv. and is the best technology, followed by water scrubbing (31,2 gCO_2-Equiv.), physical absorption (37,5 gCO_2-Equiv.) and PSA (50,5 gCO_2-Equiv.). These other emissions give anyhow the most important contribution to climate change in upgrading pathways.

5.2.4 Biogas from manure

Two pathways were analysed: biogas from wet manure and dry manure.
On the contrary, LCA does not consider the difference between dry and wet manure, that would have influenced only the emissions linked to the transport; the case of wet manure digestion in combination with both open and closed storage of the digestate are analysed instead.

5.2.4.1 CHP Pathways

- Cultivation: both default value and LCA consider 0 GHG emissions;
- Processing: RED methodology does not accounts for credits that make, in the LCA, the scenarios resulting in negative GHG production, even though this work takes into consideration also the positive emissions from digestate management (during storage, transport and spreading).
- Transport: default values are higher. LCA attributes more emissions to the pathway characterised by an open tank because of the higher requirement of manure.

RED: GHG emitted	Typical value [gCO_2eq/MJ]				Default value [gCO_2eq/MJ]			
Pathway	**Cultivation**	**Processing**	**Transport - Distribution**	**TOTAL**	**Cultivation**	**Processing**	**Transport - Distribution**	**TOTAL**
Biogas from wet manure	0,0	5,0	1,6	**6,6**	0,0	6,0	1,9	**7,9**
Biogas from dry manure	0,0	5,0	0,5	**5,5**	0,0	6,0	0,8	**6,8**
Biogas from maize as whole plant	14,3	5,0	0,0	**19,3**	17,2	6,0	0,0	**23,2**
Biogas from maize as whole plant - organic	10,7	5,0	0,0	**15,7**	12,8	6,0	0,0	**18,8**

Table 55 - Typical and default GHG emissions from biogas production [29]

RED: GHG emitted/MJ_{el}	Typical value [gCO_2eq/MJ_{el}]				Default value [gCO_2eq/MJ_{el}]			
Pathway	**Cultivation**	**Processing**	**Transport - Distribution**	**TOTAL**	**Cultivation**	**Processing**	**Transport - Distribution**	**TOTAL**
Biogas from wet manure	0,0	19,2	6,2	**25,4**	0,0	23,1	7,3	**30,4**
Biogas from dry manure	0,0	19,2	1,9	**21,2**	0,0	23,1	3,1	**26,2**
Biogas from maize as whole plant	55,0	19,2	0,0	**74,2**	66,2	23,1	0,0	**89,2**
Biogas from maize as whole plant - organic	41,2	19,2	0,0	**60,4**	49,2	23,1	0,0	**72,3**

Table 56 - Typical and default GHG emissions from biogas production and 36% electrical efficiency

LCA: GHG emitted/MJ_{el}	[gCO_2eq/MJ_{el}]				
Pathway	**Cultivation**	**Processing**	**Transport - Distribution**	**Other processes**	**TOTAL**
Biogas from manure – open storage	0,0	-224,1	2,0	30,9	**-191,1**
Biogas from manure – closed storage	0,0	-388,1	1,9	30,9	**-355,4**
Biogas from maize – open storage	40,9	66,0	1,7	31,4	**140,1**
Biogas from maize – closed storage	39,8	16,8	1,6	31,3	**89,5**

Table 57 - Emissions from biogas production and utilization to produce 1 MJ_{el}, as calculated in this study

RED: GHG emitted/MJ_{th}	Typical value [gCO_2eq/MJ_{th}]				Default value [gCO_2eq/MJ_{th}]			
Pathway	**Cultivation**	**Processing**	**Transport - Distribution**	**TOTAL**	**Cultivation**	**Processing**	**Transport - Distribution**	**TOTAL**
Biogas from wet manure	0,0	5,9	1,9	**7,8**	0,0	7,1	2,2	**9,3**
Biogas from dry manure	0,0	5,9	0,6	**6,5**	0,0	7,1	0,9	**8,0**
Biogas from maize as whole plant	16,8	5,9	0,0	**22,7**	20,2	7,1	0,0	**27,3**
Biogas from maize as whole plant - organic	12,6	5,9	0,0	**18,5**	15,1	7,1	0,0	**22,1**

Table 58 - Typical and default GHG emissions from biogas production and 85% of thermal efficiency

LCA: GHG emitted/MJ_{th}	[gCO_2eq/MJ_{thl}]				
Pathway	**Cultivation**	**Processing**	**Transport - Distribution**	**Other processes**	**TOTAL**
Biogas from maize – closed storage - CHEM	18,2	8,2	0,7	17,6	**44,7**
Biogas from maize – closed storage –PHY	16,9	7,5	0,7	37,5	**62,5**
Biogas from maize – closed storage – PSA	16,7	7,3	0,7	50,5	**75,2**
Biogas from maize – closed storage - PWS	16,2	7,1	0,7	31,2	**55,1**

Table 59 - Emissions from biogas production and utilization to produce 1 MJ_{th}, as calculated in this study

5.2.5 Fuel comparator

Both for electricity and for heat production, the fuel comparator chosen for the LCA (representing the reference system) emits lower gCO_2eq, since it considers also renewable energies that are able to avoid GHG emissions. This results in lower GHG savings, but this choice can be considered conservative.

Emission of fuel comparator [gCO_2eq/MJ]	LCA	COM(2010)11
Electricity	135	198
Heat	77	87

Table 60 – Emissions of the fuel comparator in this LCA and in the COM(2010) 11 [gCO2eq]

5.2.6 The sustainability according to the RED

As explained before, the RED sets 35% as the minimum percentage of GHG savings that could allow Member State to consider a technology environmentally sustainable and to include it in programs of renewable energies.

With the assumptions and considerations made until now, Table 61 and Table 62 represent the GHG savings for each LCA and COM(2010)11 pathways of biogas production and utilisation, according to both the fuel comparators of the two methodologies.

	Pathways	GHG savings (fuel comparator: 135 gCO2-Equiv./MJ_{el})	GHG savings (fuel comparator: 198 gCO2-Equiv./MJ_{el})
LCA	Grass, closed storage (III-B)	14%	41%
	Grass, open storage (III-A)	-28%	13%
	Maize, closed storage (I-B)	34%	55%
	Maize, open storage (I-A)	-4%	29%
	Co-digestion, closed storage (IV-B)	101%	100%
	Co-digestion, open storage (IV-A)	45%	63%
	Manure, closed storage (II-B)	363%	279%
	Manure, open storage (II-A)	241%	197%
Default values COM(2010)11	Biogas from wet manure	78%	85%
	Biogas from dry manure	81%	87%
	Biogas from maize as whole plant	34%	55%
	Biogas from maize as whole plant - organic	47%	63%

Table 61 – GHG savings for electricity production with biogas, according to COM(2010)11 and LCA metodologies

Table 62 shows that with the fuel comparator chosen for this LCA, only manure and co-digestion pathways results in sufficient GHG savings in electricity production. The higher comparator defined in COM(2010)11 allow to consider sustainable all the pathways except for the digestion of energy crops with an open storage of digestate.

In Table 62, the situation concerning upgrading pathways is represented. Grass and maize digestion is suitable for few LCA cases, while manure and co-digestion are able to guarantee high GHG savings. The pathways analysed in COM(2010)11 are acceptable in every circumstance.

Pathways	**GHG savings (fuel comparator: 77 gCO2-Equiv./MJ$_{th}$)**				**GHG savings (fuel comparator: 87 gCO2-Equiv./MJ$_{th}$)**			
Upgrading technology	CHEM	PHY	PSA	PWS	CHEM	PHY	PSA	PWA
Grass, closed storage	26%	4%	-12%	15%	35%	15%	1%	24%
Maize, closed storage	42%	19%	3%	29%	49%	28%	14%	37%
Co-digestion, closed storage	96%	69%	52%	77%	97%	73%	58%	80%
Manure, closed storage	310%	268%	249%	267%	287%	249%	232%	249%
Biogas from wet manure	88%				89%			
Biogas from dry manure	90%				91%			
Biogas from maize as whole plant	65%				69%			
Biogas from maize as whole plant - organic	71%				75%			

Table 62 - GHG savings for biogas upgrading and heat production, according to COM(2010)11 and LCA metodologies

6
CONCLUSIONS

With a Life Cycle Assessment methodology, this study evaluated the environmental performance of different biogas scenarios, from cradle (feedstocks production) to grave (biogas utilisation) in the European context. This LCA recognized the indication of the International Standardisation Organisation implemented in the EU International Reference Life Cycle Data System (ILCD) Handbook.

The first fundamental step consisted in creating complete processes and pathways considering on the whole the main emerging issues in Europe linked to biogas production and utilisation that previous LCA neglected:

- The upgrading phase with different technologies having various methane leakages and energy consumptions;
- The recirculation of nutrients in digestate management, because digestate composition, linked to the raw material composition, affects the potential to substitute chemical fertilisers and the emissions of gases in the environment;
- The account of the credits in manure pathways, that consists in considering that the anaerobic digestion avoids the emissions that would occur in the management of the raw material.

Data were collected in international literature or in European databases in order to integrate and complete Ecoinvent 2.2 considering the most common techniques and technologies used in the biogas systems.

Hereafter, the most important results are summarised.

Even though the environmental policies encourage biogas production and utilisation in order to assure GHG savings, in real plants some techniques are responsible for higher emissions than the reference system.

- The study confirmed that GHG savings can be found considering scenarios in which the digestate is stored in a closed tank before being spread on agricultural fields during the fertilising season and in which the additional biogas produced in the same tank is recovered. The results in terms of GHG savings are the followings:
    - For CHP pathways:14,2% grass digestion, 33,8% maize digestion, 100,6% co-digestion, 363% manure digestion.

- For upgrading pathways, results are reported in Figure 71 that shows also the role of the different technologies. The pathway with PSA and grass digestion cause higher GHG emissions than the reference system.

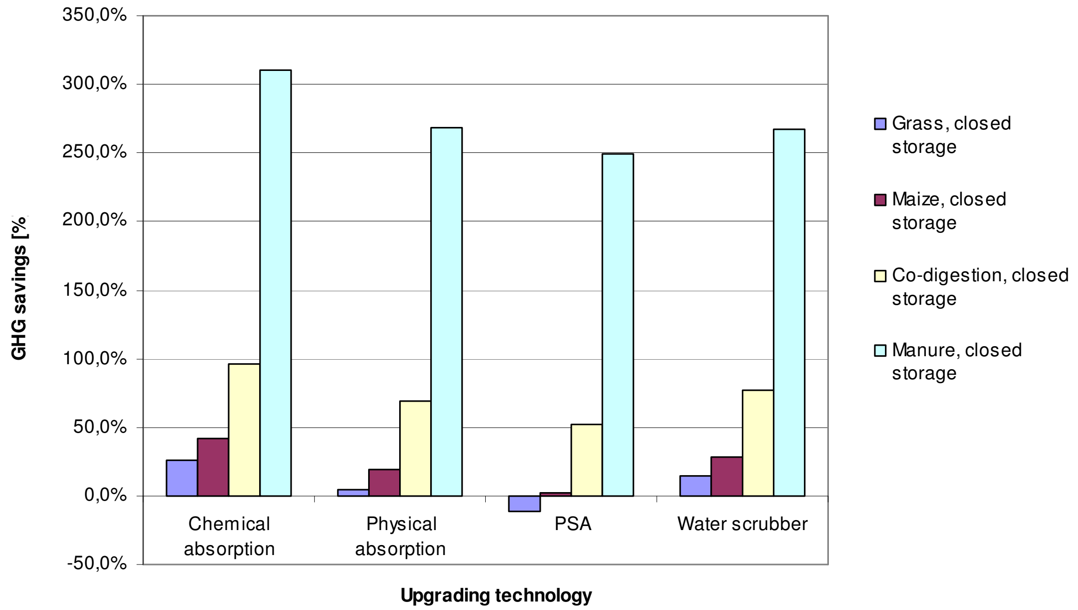


Figure 71 – GHG savings of different feedstocks in upgrading pathways

- If the storage tank of digestate is open, all these savings are lost and the impact on climate change is even higher then the reference system because of the large emissions in the atmosphere of methane and nitrous oxide. Only scenarios with manure as feedstock (both alone and co-digested with maize) remain sustainable thanks to the assigned credits. GHG savings are the following: -27,6% grass silage, -3,6% maize silage, 45,3% co-digestion, 242,3% manure.

- Figure 71 illustrates that the discrepancy between the upgrading technologies is due to methane leakages: the higher is the CH_4 leakage, the higher are the GHG emissions. Chemical absorption should be preferred since it emits only 0,1% of the methane produced, followed by water scrubbing (2%), physical absorption (3%) and PSA (5%). It is therefore essential to specify the type of upgrading technology considered, as this LCA has done for the first time. If the most appropriate digestate management technique is used, the sustainability of the pathways is achieved also if the methane leakages exceed the values guaranteed by the constructors. It is recommended to verify that these emissions are lower than 5,5% of the methane recovered, since that could occur according to measurements in real plants [41]. If leakages are high, benefits can be found in flaring the off-gas of the upgrading step in order to convert the lost methane into biogenic carbon dioxide.

- The uncertainties linked to the attribution of N_2O emissions to the digestate could lead to over- or underestimate the GHG emissions of the pathways. In literature, no agreement was found concerning these emissions. Calculations starting with literary data about the emissions of N_2O from digested manure in spreading resulted in a range of values between 0,000120 $kgN_2O/kg_{digestate}$ [17] and 0,0000346 $kgN_2O/kg_{digestate}$ [20].

This LCA showed also the potential impacts on other environmental categories. The results underlined that even if a pathway has a positive effect on climate change, it can have higher environmental impacts than the conventional energy production system on other areas of protection such human and eco-toxicity, euthophication etc, as reported below.

- Biogas pathways in which energy crops are anaerobically digested score worse than the reference system considering human toxicity, particulate matter formation, photochemical ozone formation, acidification, eutrophication, ecotoxicity and resource depletion. The causes are correlated to the cultivation processes, to the emission from the engine (in CHP pathways) and to electricity taken from the grid (required in upgrading pathways).

- Little benefits could be found in all the CHP pathways only regarding stratospheric ozone depletion (between -2% in case of maize with open storage of digestate and -43% for manure digestion), while the impact on ionising radiation is more than 95% lower because of radioactive material linked to the nuclear share in the European electricity production.
In upgrading pathways emissions are from 83% to 92% lower than the reference system only according to ozone depletion.

- Manure is the most suitable feedstock because it does not require a cultivation process, but results are strongly dependent on the account of the credits that take into account the avoided emissions of the storing and spreading of the undigested material. Beside reaching the highest GHG savings, its pathways remain inside the sustainability boundaries with reference to many categories:
  - CHP pathways: PM-intake (-26%), and acidification (-137%), the both only in closed digestatate configuration; freshwater eutrophication (-128%), terrestrial ecotoxicity (-52%),
  - Upgrading pathways and digestate in closed configuration: marine eutrophication (between -119% a -143%, according to the type of the technology), photochemical ozone formation ([-46%;-76%)]), PM-intake ([-498%;-560%]) and acidification ([-677%;-731%]).

- Cultivation is the process of the life cycle the most responsible for high impacts (i.e. in ecotoxicity, eutrophication, acidification). This is the reason why, for example, decreasing the utilisation of chemical fertilisers can reduce the global emissions. The lowest is the agricultural effort made to produce the feedstock, the lowest are the GHG emissions, because of machinery manufacturing and use as well as fertilisers and pesticides production and utilisation. Since grass has a low biomass yield per hectare (29,1 t/ha compared to 42,5 t/ha of maize) these practices are responsible for higher GHG emissions than the other feedstocks.

- Little differences appear among the upgrading technologies. When the cultivation is the most significant process in causing the emissions, chemical absorption pathways have higher emissions because this pathway requires more biomass in input to reach the same functional unit, due to the requirement of heat inside the technology (i.e. in acidification potential, PM formation, eutrophication). On the contrary, because of the lower electricity consumption, this technology has the best performance when the electricity taken from the grid is the main emission source (i.e. ionising radiation). In these cases, PSA score worse.

- Electricity generation is the best way to use biogas because less impact categories result in higher impacts than the reference system. Indeed, the fuel comparator used comprehends also European technologies responsible for high emissions of different compounds and therefore many impacts, i.e. coal and lignite combustion and nuclear energy. Moreover, with the opportunity to deliver for district heating the heat produced with the engine, additional benefits are supposed to occur since this method allows avoiding heat production with traditional fuels.

- On the contrary, the production and utilisation of biomethane is compared with the same service provided by natural gas that is one of the cleanest ways to produce energy with a fossil fuel. Therefore, biogas pathways results in higher impacts.

- The comparison between the results of this LCA and the typical and default emission values for biogas production reported in the COM(2010)11 that integrates the Renewable Energy Directive showed that this methodology avoids to consider important issues such as:
    - the GWP_{100} values recommended by the latest report of the IPCC [44]
    - Differences between closed and open storage of digestate;
    - Machinery production;
    - Manure credits;
    - Leakages occurring in the devices used to produce the final energy;
    - Emerging feedstocks suitable for digestion, such as grasses, and the possibility to co-digest different agricultural biomasses.

It is therefore recommended that an eventual update of such default and typical values would consider all these issues. In fact, according to the results found in this LCA, only the pathways in which manure is among the feedstocks can be always considered suitable to be accounted for in the environmental policies of Member States, since they can guarantee GHG savings higher than 35%.

6.1 OTHER INTERESTING OPEN ISSUES

- The inclusion of the problem of the direct (**dLUC**) and indirect land use change (**iLUC**), as recommended by IEA Bioenergy [43] should be considered in a subsequent study: the second contribution is particularly interesting since this represents a new and complex area of research, involving the need to integrate a number of policy considerations, different stakeholders and different regions.

- Fields research should be performed in order to understand the **composition of the digested material** that originates after the process of biogas production starting from different raw materials. These results will lead to a better understanding of the nutrient recirculation and asset the most adequate fertilising programs. During this work, it was also calculated that about 25% of the carbon content of the plant is likely to remain in the digested material. This issue should be analysed deeper in order to evaluate the possibility to consider also these carbon credits.

- The decision about **what technology is more suitable** to be substituted by biogas depends also on political, economic and strategic matters that are not analysed in this project, since this LCA modelling is only attributional.

- In order to evaluate the best use for biogas and biomethane, a pathway for biomethane used as **transportation fuel** could be considered.

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