# Life cycle assessment of conventional and advanced two-stage energy-from-waste technologies for methane production

C. Tagliaferri[1,2], S. Evangelisti[1], R. Clift[3], P. Lettieri[1]*

C. Chapman[2], Richard Taylor[2]

[1]Department of Chemical Engineering, University College London, Torrington Place London WC1E 7JE, UK.

[2]Advanced Plasma Power (APP), Unit B2, Marston Gate, South Marston Business Park, Swindon, SN3 4DE, UK.

[3]Centre for Environmental Strategy, The University of Surrey, Guildford, Surrey, GU2 7XH, UK

*Corresponding author: Email: p.lettieri@ucl.ac.uk; Phone: +44 (0)20 7679 7867

**Abstract**

This study integrates the Life Cycle Assessment (LCA) of thermal and biological technologies for municipal solid waste management within the context of renewable resource use for methane production. Five different scenarios are analysed for the UK, the main focus being on advanced gasification-plasma technology for Bio-Substitute natural gas (Bio-SNG) production, anaerobic digestion and incineration. Firstly, a waste management perspective has been taken and a functional unit of 1 kg of waste to be disposed was used; secondly, according to an energy production perspective a functional unit of 1 MJ of renewable methane produced was considered. The first perspective demonstrates that when the current energy mix is used in the analysis (i.e. strongly based on fossil resources), processes with higher electric efficiency determine lower global warming potential (GWP). However, as the electricity mix in the UK becomes less carbon intensive and the natural gas mix increases the carbon intensity, processes with higher Bio-SNG yield are shown to achieve a lower global warming impact within the next 20 years. When the perspective of energy production is taken, more efficient technologies for renewable methane production give a lower GWP for both current and future energy mix. All other LCA indicators are also analysed and the hot spot of the anaerobic digestion process is performed.

**Keywords:** Advanced thermal treatment, anaerobic digestion, mechanical biological treatment, life cycle assessment, municipal solid waste, future energy scenarios.

## Highlights

- When the electricity mix is highly carbonised waste-to-electricity determine a lower impact than waste-to-methane
- The GWP of bio-SNG production from waste decreases for future UK energy scenarios
- Opposite results are reported when the emphasis is on energy production rather than waste management

## 1.1 Introduction

Increasing environmental awareness has pushed European governments to impose binding targets to increase the share of renewable energy consumption and decrease carbon emissions. According to the articles 8 and 9 of the Renewable Energy Directive (RED) (European Commission, 2009), the UK is committed to be utilising 15% of its energy (that includes heat, electricity and energy for transport (HM UK Government, 2009; UK Government, 2009)) from renewable resources by 2020. Further targets have also been put in place in 2014 (European Council, 2014): by 2030 greenhouse gases are to be reduced by at least 40% compared to 1990 and at least 27% of energy has to be renewable.

For the development of renewable energy, the financial support and the development of emerging technologies are considered fundamental (UK Government, 2009). The UK government introduced the renewable obligations (2002) and the Feed-in tariffs for electricity generation (2010), the Renewable Heat Incentives (2011) for heat production and the Renewable Transport Fuel Obligation (2007) for road transport fuel sales as financial incentives to meet the renewable energy targets.

The production of energy from waste is reported (REA, 2011) to have a significant role in the renewable energy sector because alternative waste management options can reduce the environmental impact of waste disposal and produce economic opportunities and growth (Communities and local Government, 2011). Therefore, production of energy such as electricity and bio-fuels, from waste is eligible for financial support within the renewable schemes to actively promote growth in this sector.

One possible route that is later analysed in this study, is the use of municipal solid waste (MSW) to produce renewable methane as this is also eligible for financial support. The production of renewable methane is reported to be a key factor for the UK to meet the 2020 and 2030 targets (DECC, 2011). National Grid (2014) reports that the production of biomethane/bio substitute natural gas (Bio-SNG) from renewables will become an important part of the future UK natural gas mix.

However, when waste is treated in alternative technologies, such as those reported by Panepinto (2014) and Hu (2015), and a deviation from the waste hierarchy (Defra, 2011) is applied, Life Cycle Assessment (LCA) should be used to assess the environmental burdens of the developing alternatives (European Commission, 2003). Extensive LCA work is needed to assess the environmental performance of gas production from the renewable source of waste, including thermal and biological technologies. In particular, the technological and environmental assessments of thermal technologies -mainly gasification- treating MSW for Bio-SNG production are rarely analysed in literature, whereas more studies focus on the analysis biological processes treating biomass, including, for example, anaerobic degradation processes of the liquid fraction of pressed solid waste (Koók et al., 2016; Rózsenberszki et al., 2015).

Very few studies report on the technological performance and energy efficiency of methane production from MSW gasification: for example, Sues et al. (2010) modelled different routes for the production of bio-fuels, including, between others, SNG from MSW and other feedstocks to identify the mass conversion and energy efficiency of each process. Moreover, Juraščík et al. (2010) and Vitasari et al. (2011) presented the analysis of the energy efficiency of SNG production from wood gasification.

To the authors' knowledge, no studies report on environmental assessment of thermal technologies for methane production from the entire fraction of municipal waste. Conversely, wood and agricultural biomass (Felder and Dones, 2007; Hacatoglu et al., 2010; Pucker et al., 2012; Steubing et al., 2011) and also manure (Luterbacher et al., 2009) treated in gasification technologies are usually considered. For wood waste, Felder and Dones (2007) and Steubing et al. (2011) showed that the impact of the entire life cycle of the SNG process, from wood growth to heat and electricity production, was mainly due to the SNG production stage: the low overall chain efficiency of the SNG production process, resulting from additional processing, and the need for substantial energy for gas compression, limited the performance of the SNG system when compared with fossil alternatives.

Furthermore, many LCA studies on waste management assess the environmental impact of a single technology only, either biological (anaerobic digestion) (Boldrin et al., 2011; Evangelisti et al., 2014a, 2014b; Lundie and Peters, 2005; Mezzullo et al., 2013) or thermal (Consonni et al., 2005a, 2005b; Evangelisti et al., 2015) and accordingly a single feedstock and product is analysed. Conversely, Hospido et al. (2005) analysed the environmental impacts associated with disposal of sewage sludge through anaerobic digestion or thermal processes but only pyrolysis and incineration were considered.

This study presents the LCA of an advanced novel thermal technology treating the entire fraction of MSW for production of methane. Waste is first transformed into a clean syngas in an advanced dual stage gasification and plasma technology (Evangelisti et al., 2015); then, methane is produced using the technologies of water gas shift and methanation. Those two technologies are already widely used in industry, for example, for production of hydrogen from fossil resources and ammonia (Appl, 2000; Boll et al., 2000) but they have never been previously proven for the production of methane from MSW.

This technology is compared to biological alternatives including i) mechanical pre-treatment of MSW associated with the anaerobic digestion of the organic fraction and landfill/incineration of residual waste; ii) anaerobic digestion of source separated waste and landfill/incineration of residual waste.

Two different perspectives are analysed in this study: a waste management and an energy production perspective, where two different functional units are used, 1 kg of waste treated and 1 MJ of gas produced, respectively. For each perspective (1kg of MSW and 1 MJ of methane produced), the comparison is firstly performed considering the current UK energy mix and then extended to include future energy mix scenarios in the UK.

To the authors' knowledge, this is the first paper which attempts to analyse the impact of developing thermal and biological systems treating MSW for renewable methane production in the context of future energy scenarios. This work, focusing on Bio-SNG production from waste and future energy mixes, complements and expands previous work by Evangelisti et al. (2015) which focused solely on the production of electricity from waste in the current energy mix framework.

Furthermore, it is worth emphasizing that whilst many studies dealing with the environmental impact of waste to energy systems often analyse only the greenhouse gas emissions (Astrup et al., 2009; Mohareb et al., 2008; Tan et al., 2014; Zhao et al., 2009), this study presents a complete environmental assessment including a wide range of environmental impacts.

**1.2 LCA methodology**

Life cycle assessment is one of the most developed and widely used environmental methodology for comparing alternative processes or services. Life cycle assessment systematically analyses the entire life cycle of goods and services from raw material extraction to the product final disposal, including manufacturing, transport, use, re-use, maintenance and recycling, i.e. all flows to and from nature are assessed under a 'cradle to grave' perspective (Baumann and Tillman, 2004). Moreover, it helps to determine the ‘‘hot spots’’ in the system, that are those activities that have the most significant environmental impact and should be improved as the first priority, thus enabling identification of more environmentally sustainable options (Clift, 2006).

The LCA methodology consists a four very distinct phases. In the goal and scope definition the purpose of the study is primarily defined but also the following points should be addressed: i)what political or technical decision will depend on the results of the study; ii)what are the system boundaries for the study iii) what is the basis for comparison between different alternatives (i.e. which is the functional unit). During the inventory phase a life-cycle model of the product of interest is built up and all the environmentally relevant inputs and outputs of the process are listed. The inputs and outputs of each unit operation in the model are quantified and identified as either resource use or emissions (emissions to soil, water and air). In the impact assessment phase the energy and mass flows are translated into potential impacts (referred to as environmental indicators) to the environment. According to its mass flow each environmental intervention is transformed into an environmental burden through a common unit, specific for the environmental category. Normalization and weightening are also included in this phase. The last phase includes the analysis of the results and the assessment of the conclusions based on the points reported in the goal and scope definition.

In LCA, a multifunctional process is defined as an activity that fulfils more than one function, such as a waste management process dealing with waste and generating energy (Ekvall and Finnveden, 2001). It is then necessary to find a rational basis for allocating the environmental burdens between the functions. The problem of allocation in LCA has been the topic of much debate (Clift et al., 2000; Heijungs and Guinée, 2007). The ISO standards (ISO 14040, 2006) recommend that the environmental benefits of recovered resources should be accounted for by broadening the system boundaries to include the avoided burdens of conventional production (Eriksson et al., 2007). This approach is applied in this study.

Following the methodological approach of Clift et al. (2000) a distinction is made between Foreground and Background, considering the former as ‘the set of processes whose selection or mode of operation is affected directly by decisions based on the study’ and the latter as ‘all other processes which interact with the Foreground, usually by supplying or receiving material or energy’. The burdens are evaluated under three categories (Clift et al., 2000): direct burdens, associated with the use phase of the process/service; indirect burdens, due to upstream and downstream processes (e.g. energy provision for electricity or diesel for transportation); and avoided burdens associated with products or services supplied by the process (e.g. energy or secondary material produced by the system).

When translating the inventory data in environmental impacts, two general approaches are available, the so-called mid-point or end-point (Clift, 2013). In this study the mid-point approach is used and inputs are expressed in terms of their contribution to a set of impact mid-point categories. The standard mid-point impacts used in this study are those defined by Guinée (2002) and are described in the supplementary information. The study focusses on six impact categories which are found to be most significant for the comparison between the different processes, as shown in the normalized results presented in the Supplementary Information.

Currently more than thirty software packages exist to perform LCA analysis, with differing scope and capacity: some are specific for certain applications, while others have been directly developed by industrial organisations (Manfredi and Pant, 2011). In this study GaBi 6 has been used (Thinkstep, 2015). GaBi 6 contains databases developed by Thinkstep, it incorporates industry organisations' databases (e.g. Plastics Europe, Aluminium producers, etc.) and also regional and national databases (e.g. Ecoinvent, Japan database, US database, etc.).

Further information on the methodology is reported in the supplementary information.

## 2. Goals and Scope Definition

### 2.1. System boundaries

The analysis starts from the waste stream (referred to as MSW in this study) exiting a material recovery facility (MRF), through to the production of methane suitable for grid injection according to the Gas Safety Management Regulation (GSMR, 1996). The life cycle of the waste streams separated from the residual waste is omitted in this assessment as assumed to be identical in all scenarios investigated.

We analyse 5 different scenarios, as shown in Figure 1:

1. In scenario 1 (S.1), the residual waste is assumed to be mechanically sorted and then the centrally separated organic fraction is biologically treated in an anaerobic digestion plant at the same site. The separated non biodegradable waste is partially recycled and partially sent to incineration as later specified.
2. Scenario 2 (S.2) is the same as scenario 1 but the separated waste is assumed to be partially recycled and partially sent to landfill as later specified.
3. In scenario 3 (S.3) we account for a higher source separation of bio-degradable waste and therefore the organic fine fraction of the residual waste is assumed to be source separated and treated in an AD plant whereas the rest is sent directly to incineration without further treatment.
4. Scenario 4 (S.4) is the same as scenario 3 but residual waste is assumed to be sent to landfill.
5. In scenario 5 (S.5) the waste is treated in an advanced thermal treatment technology, such as a two stage gasification and plasma process, based on a technology developed by industrials (Advanced Plasma Power, 2015).

Figure 1 shows the system boundary of this analysis and identifies the different scenarios, where circles identify flows whereas squares identify processes. Indirect activities of the supply chains and waste disposal processes constitute the background, whereas the scenarios investigated are the foreground. Avoided burdens are allocated to valuable substances production/recovery and emissions and residual waste material disposal are included in the assessment.

The main goals of this work are:

- To compare the environmental burdens of the different scenarios analysed and identify the hot spots.
- To compare the environmental burdens of the scenarios analysed according to the UK future foreseen energy mixes, till 2035 (National Grid, 2014).
- Assess the impact of the functional unit on the results according to two different approaches, the methane recovery and the waste management perspectives.

- To compare the environmental impacts of the anaerobic digestion process treating source-separated waste against centrally separated waste.

### 2.2. Functional Unit

Two different perspectives are analysed in this work. Hence, the results are reported according to the functional unit of 1 kg of MSW and 1 MJ of methane produced. When 1 kg of MSW is chosen as functional unit, the targeted question that the analysis is trying to answer is 'what is the best waste management option given a certain amount of MSW?' On the other hand, when 1 MJ of clean gas produced is chosen as functional unit, the study is trying to answer the following question 'what is the best technology for the production of a given amount of methane?' A key factor that differentiates the technologies analysed is the efficiency in methane production, Table 1 reports the yield in methane production for the scenarios analysed.

## 3. Life Cycle Inventory

### 3.1. Life Cycle assessment models

The inventories of the processes analysed have been collected for commercial scale plants. Both the primary and secondary data used are regionalized and refer specifically to the UK. Key inventory data are reported in Table 2 and further analysed in the following paragraphs and in the supplementary data. The models for incineration and landfill have been built according to GaBi database (Thinkstep, 2015) and more information on those two processes and transport of waste is reported in the supplementary data.

The residual waste composition and its heating value are reported in Table 3; they are based on typical waste collected in south-west England. The same waste composition is assumed for all the scenarios analyzed.

#### 3.1.1. System expansion

In scenarios 1, 2 and 5 the metals (ferrous and non-ferrous) are mechanically separated from MSW and recovered for future reprocessing and final sale as recycled metals. Therefore, avoided burdens are allocated to those processes according to the models already reported in Evangelisti et al. (2015).

In scenario 1 and 3 electricity is recovered from the incineration of waste; in scenario 5, electricity is produced from the off gas of the Bio-SNG upgrading; in scenarios 2 and 4 electricity is recovered from captured landfill gas. Avoided burdens are allocated to the production of electricity based on an average mix of technology in the UK (Thinkstep, 2015).

Avoided burdens have also been allocated to the production of upgraded methane because this is assumed to be injected into the grid and to substitute the UK natural gas mix (Thinkstep, 2015).

In paragraph 4.4, the current energy mix is substituted with future energy shares according to National Grid (2014).

### 3.2. Anaerobic Digestion of centrally separated waste (S.1 and S.2)

Archer et al. (2005) and Guinan et al. (2008) refer to one particular layout of the MBT where no aerobic composting is used but the process is designed to deliver biogas using AD. AD cannot be directly applied to the entire fraction of MSW, therefore a mechanical treatment is needed to apply AD only to the organic fraction of the centrally separated MSW. In this case, extensive physical/mechanical separation and pre-treatment is always necessary prior to digestion (Monson et al., 2007).

Many LCA studies analyse the impact of mechanical biological waste treatment (MBT) where the biological process is aerobic composting (Arena et al., 2003; Buttol et al., 2007; Consonni et al., 2005a, 2005b; Esmaeil et al., 2012; Hong et al., 2006). Conversely, very limited work has been done on the environmental impact of MBT processes where the biological treatment is AD. Some report on the software tools that can be used to calculate the burden of this process (den Boer et al., 2007); few others report the results of the greenhouse gas impact (Baddeley et al., 2010) but none performs a comprehensive LCA study from cradle to grave, looking at all different environmental impacts.

Literature data have been used to build the models for scenarios 1 and 2 as referred in Table 2; the high level diagrams of those scenarios are reported in Figure 2. The outputs of the mechanical separation are assumed to be i) organic fraction suitable for biological treatment in an AD plant; ii) recovered metals suitable for reprocessing and sales in the market; iii) inert material used as landfill cover; and iv) residual waste containing the remaining not separated MSW fractions sent either to incineration (scenario 1) or landfill (scenario 2). The unsorted remaining fractions are not transformed into RDF but are directly sent to the disposal facilities; no pelletizing is assumed as also reported in Consonni et al. (2005b). Defra (2013) reports that recyclables (such as plastic and card) derived from the various MBT processes are typically of a lower quality than those derived from a separate household recyclate collection system and have a lower potential for high value markets. Therefore, for many mechanical separation systems, metals (ferrous and non-ferrous) are the only recyclates always extracted (as assumed in this study). The energy consumption for the mechanical separation of waste is based on literature data (Consonni et al., 2005b; Defra, 2013; Montejo et al., 2013).

Six operations are identified in the AD process (Figure 3): i) pre-treatment; ii) anaerobic digestion; iii) water and acids removal; iv) upgrading of the biogas in a PSA system; v) disposal of digestate to incineration. The characteristics of each part and the assumptions used in the LCA models based on literature data are specified in the Table 2 and supplementary data.

### 3.3. Anaerobic Digestion of source separated waste (S.3 and S.4)

When planning for a sustainable new settlement, there is potential for increasing the sorting efficiencies (Slagstad and Brattebø, 2012). In scenarios 3 and 4 we assume that the source separation of bio-degradable waste is higher than that of scenario 1 and 2 and this amount of waste is treated in an AD plant. The residual waste is assumed to be sent to incineration (scenario 3) or landfill (scenario 4). The high level diagrams of S.3 and S.4 are reported in Figure 3.

The substrate of the anaerobic digestion is kitchen source separated waste, its composition is reported in Banks et al., (2011); this is the substrate that determines the highest yield in biogas production. No card and paper are assumed to be anaerobically digested. As the waste is separated at source, the amount of mechanical separation and pre-treatment required (and thus the complexity and cost of the system) is reduced, although some mechanical separation is always necessary.

The model of AD for scenarios 3 and 4 is the same as the model used for scenario 1 and 2 except for the assumptions regarding the biogas yield and the digestate use. The raw biogas production has been assumed to be 0.14 $Nm^3$ per kg of bio-degradable fraction of MSW (wt%), based on literature data (Banks et al., 2011; Evangelisti et al., 2014a; Moller et al., 2007; Robertson et al., 2010). The whole digestate is separated in liquor and fibre as standard practice reported in Wrap (2012) and the analysed separation method is physical (Wrap, 2010). The liquor separated from the whole digestate in the dewatering process is used as fertilizer, whereas the fibres are sent to incineration as inert material (Wrap, 2012). The system boundaries are expanded to include the avoided burdens allocated to the substitution of chemical fertilisers, and to the amount of carbon sequestered in the soil when the digestate is used as chemical fertilizer (Moller et al., 2007). The emissions due to the organic fertilizers when those are on the soil are also included in the inventory. Further assumptions regarding the model are specified in Table 2 and in the supplementary data.

### 3.4. Advanced thermal treatment: dual stage gasification and plasma process (S.5)

The dual stage gasification and plasma technology for Bio-SNG production from MSW is a novel advanced thermal conversion technology currently under development (Advanced Plasma Power, 2015; Chapman et al., 2014; Ray et al., 2012; Taylor and Chapman, 2012; Taylor et al., 2013). The high level diagram of this process is shown in Figure 4.

The advanced technology is a highly flexible two-stage thermal process, capable of treating a wide range of organic and inorganic wastes including Municipal Solid Waste and Refuse Derived Fuel (RDF). Pre-treatment of the received waste includes shredding, drying and mechanical metals recovery, sold as recyclates. The core of this technology comprises a two-stage thermal treatment system. The fluidised bed gasifier using oxy-steam converts the prepared non–pelletized RDF to a raw syngas containing significant levels of char, ash, tars and other liquid organic contaminants. This gas stream, together with the char and ash product from the gasifier, is then treated in a high temperature plasma converter unit. It efficiently cracks problematic tars in the raw syngas to produce a reformed quality synthetic gas. The inorganic ash fraction from the gasifier is vitrified in the plasma converter unit to produce a dense, stable vitrified product, which can be used as aggregate in road construction. The syngas, after cooling, Air Pollution Control removal (APC), tertiary cleaning of the acid gases and further polishing in a guard bed, is suitable for catalytic conversion to Bio Substitute Natural Gas (Bio-SNG). A high temperature water-gas shift adjusts the stoichiometric ratio $H_2/CO$ in the syngas to around 3:1, as required at the methanator stage. After the final polishing in a ZnO guard bed, the compressed gas is injected into the methanator reactor where the raw Bio-SNG is produced. This is upgraded in a Pressure Swing Adsorber (PSA) system and injected into the grid. The low quality combustible gas (mainly mix of $CH_4$ , $H_2$ and inert) recovered in the PSA system is used to produce electricity and the off gas is flared and emitted to the environment. The heat produced through the process which is not used for serving the internal requirement, is assumed to be used for electricity production in a steam turbine. The solid fuel preparation, syngas generator and syngas refining units (see Figure 4) are modelled as reported in Evangelisti et al. (2015). Further inventory data for the LCA model of this process are based on experimental and modelling data provided by industrial developers and are reported in Tables 2-3 and in the supplementary data.

## 4. Results and discussions

In this section, the scenarios analysed are compared according to the two different approaches described in 2.2. Generally, the results of a LCA analysis do not draw a unique guideline for the environmental problems analysed; conversely, given results, analysed under different perspectives, can propose different solutions and interpretations for the same system. It will be shown that multiple and sometimes controversial conclusions and guidelines can be drawn depending on the approached problem. The perspectives analysed will mainly depend on the system boundary considered and on the environmental problems tackled; the results have to be read and analysed according to a specific context. The functions that the specific systems deliver are other key aspects for the interpretation of the results; these are strictly linked with the chosen functional unit of the system and the goals of the study.

### 4.1 What is the best waste management option for waste disposal?

The following results are reported according to the functional unit of 1 kg of MSW. Therefore, the approached perspective is looking at the problem of waste management and disposal.

Figure 5 shows a comparison of the environmental impacts associated with the five scenarios analysed for 1 kg of MSW as functional unit. These results have been obtained using the current energy mix of the UK in the LCA models of indirect and avoided burdens. Only significant results are shown here, although the analysis was performed for more indicators as shown in the supplementary data where normalised results are presented. It is not possible to identify a unique best scenario as the aspects influencing each indicator are different as explained in the following paragraphs. However, the scenarios where the metal recovery is considered show a better environmental performance for all the indicators analysed, except FAETP and ODP as shown in Figure 5. Those two latter indicators are driven by other factors as reported in the discussion of the results.

#### 4.1.1 Comparison of scenarios 1, 3 and 5

Figure 5 shows, among others, the environmental impacts of scenarios 1, 3 and 5 for 1 kg of MSW. The results do not show a unique trend for all the indicators analyzed.

*GWP*. Figure 5 shows that the dual stage process is the less favourable option. The value of the GWP for each scenario primarily depends on the $CO_2$ emissions at the stack and the avoided burdens allocated to the substitution of valuable products- that also means the efficiency in electricity and renewable methane production. As the waste treated in all scenarios has the same carbon composition, the avoided burdens mainly determine the relative balance of the results. The avoided burdens allocated to the production of electricity is contributing the most to the total GWP also when they are compared to the avoided burdens allocated to methane production and metal recycling. This is due to the current highly carbonised electricity mix in the UK: the production of 1 kWh of the UK electricity mix determines 0.556 kg of $CO_2$ eq. whereas the production of 1 kWh of fossil methane determines 0.0014 kg of $CO_2$ eq. However, the production of Bio-SNG through thermal waste processes is not currently a fully developed technology but it will significantly contribute to the UK energy mix in future energy scenarios (National Grid, 2014). The latter will see an increased decarbonisation of the grid thanks to the introduction of renewable technologies and an increased footprint of the natural gas mix due to the introduction of LNG and possibly shale gas. Hence, the thermal production of Bio-SNG from waste might represent a valid alternative to decrease the burden of the UK natural gas grid mix when the analysis is performed according future energy mix (see paragraph 4.4).

*AP.* The AP (Figure 5) of scenarios 1 and 3 are both negative due to the allocation of avoided burdens to the recovery of metals and electricity production in the incineration processes. The indirect burdens related to the electricity recovery predominantly influence this indicator, whereas the avoided burdens allocated to methane production have a minor impact on the results (as also shown for the GWP). In scenario 5 the amount of electricity produced is smaller than the amount produced in scenario 1 and 3 and therefore the higher yield in methane production does not offset the positive burdens of the process. Scenario 1 shows an AP almost 3.5 times lower than the AP of scenario 3 even though its yield in methane is lower. This is due to the avoided burdens allocated to metal recovery in scenario 1 and not in scenario 3.

*ADP*. Figure 5 shows that the best option to avoid the depletion of fossil resources is the dual stage gasification and plasma process. The ADP of the advanced thermal process is 36% and 40% lower than the ADP of scenario 1 and 3, respectively. This is due to the higher yield in methane production per kg of MSW and consequently to the higher avoided burdens for methane production allocated to this process. For the ADP, hence, the aspect that determines the trend of the results is the avoided burdens allocated to the production of methane.

*FAETP*. FAETP (Figure 5) represents the most significant results within all the toxicity indicators and it has hence been chosen for discussion. Scenario 3 only shows a negative burden; this is due to the allocation of avoided burdens to the use of digestate as organic fertilizer substituting chemical fertilizer. In many LCA studies on AD (Boldrin et al., 2011; Bruun et al., 2006; Evangelisti et al., 2014a; Moller et al., 2007) the allocation of avoided burdens for chemical fertilizer substitution is considered only for the GWP. Conversely, all the indicators analyzed in this study account for these avoided burdens. Our results show how some indicators might be driven by the avoided burdens allocated to the chemical fertilizer substitution, hence for a complete LCA those impacts must be included in the study. The FAETP value of 2.29E-2 kg of DCB Eq. allocated to scenario 1 (Figure 5 ) is 100% due to the incineration of the digestate and its consequent emissions to air, water and soil through flue gas, bottom ash and APC residues disposal. Conversely, for scenario 5 the value of 4.73E-3 kg of DCB Eq. is due to upstream indirect emissions allocated to the production of chemicals used in the tertiary cleaning of the syngas.

*EP*. The significant difference in the EP (Figure 5) results -3.67E-4, 4.6E-4 and 7.79E-5 kg of phosphate Eq. for scenarios 1, 3 and 5, respectively- is mainly due to the difference in the emissions to the environment of the N compounds (see Table 4). Scenario 5 performs better than all other scenarios because the advanced thermal treatment causes lower emissions of $NH_3$. The disposal of digestate (either to incineration or as organic fertilizer for scenario 1 and 3, respectively) contributes almost wholly to this indicator. Further explanation is reported in the hot spot analysis of the anaerobic digestion.

*ODP*. Scenario 3 shows the highest ODP (see Figure 5) among S.1, S.3 and S.5 because of the lack of avoided burden allocated to the metal recovery in scenario 3. S.5 performs better than all other scenarios thanks to lower emissions.

#### 4.1.2. Comparison scenarios 2, 4 and 5

Figure 5 also reports the environmental results for scenarios 2 and 4 for 1 kg of MSW. Even if the numerical results are not the same as scenarios 1 and 3, the relative trend of S.2, S.4 and S.5 is the same as S.1, S,3 and S.5 for the ADP, AP, EP and FAETP. For these indicators, the different environmental burdens allocated to scenarios 2 and 4 due to the landfill instead of incineration do not alter the preferred environmental choice. On the other hand GWP and ODP do not show the same trend of the results.

*GWP*. When considering scenarios 1, 3 and 5 (Figure 5) the best choice to treat 1 kg of waste is scenario 1 (even if this scenario is not optimized for methane production, it is the one that determines the lowest environmental impact due to the avoided burdens allocated to electricity and metal production). Conversely, when considering scenarios 2, 4 and 5 (Figure 5), the best option is shown to be scenario 5. The methane that comes from the landfill gas released to atmosphere (which is primarily methane and carbon dioxide) is the main contributor to GWP for scenarios 2 and 4 and this gives the poorest environmental performance. For scenario 5 the main contribution to GWP is instead coming from the off gases released from the upgrading system (which is primarily carbon dioxide).

*ODP*. This is the only indicator where S.2 and S.4 perform both better than S.1 and S.3. This is due to the lower contribution of indirect chemical productions for S.2 and S.4.

ADP, AP and GWP of scenario 1 and 3 are worse than the same indicators for scenario 2 and 4 as expected (landfill is reported to have a higher environmental impact than incineration mainly because of the lower amount of energy recovered and higher emissions). However, EP and FEATP are shown to be the same for scenarios 1, 2, 3 and 4. The reason for this has to be found in the hot spot analysis of those processes (as reported in paragraph 4.4). The main contributor to the EP and FAETP is due to the digestate disposal. Therefore, the other impacts of the processes, such as landfill, incineration or recovery of valuable substances become negligible and those do not affect the results.

### 4.2 What is the best technology for production of renewable methane?

The following results are reported according to the functional unit of 1 MJ of produced methane. In this case, the analysis is focusing on the aspect of renewable energy production using different technologies. The trend of the results is the same as that of Figure 5 for all the indicators, except for the ADP and GWP (see Figure 6).

*GWP*. A change in the functional unit determines an inversion of the results for the GWP, in this case Figure 5 shows that the dual stage process is the worst option whereas this process is shown to be the preferred option in Figure 6 among the thermal processes (for the ADP it is the opposite). When the functional unit is assumed to be 1 MJ of methane injected into the grid the avoided burdens allocated to the production of methane are the same for all processes (Figure 6). The yield of methane production for the dual stage process is the highest and this corresponds to the lowest amount of MSW treated and therefore lowest direct burden of $CO_2$ for this process (emissions of $CO_2$ to the environment are based on the amount and composition of waste). For this case the avoided burdens allocated to the electricity and metal recovery do not have a significant influence on the results.

*ADP*. Figure 5 shows that the best option among the thermal treatments (S.1, S.3, S.5) is the dual stage process whereas Figure 6 shows that this process is the worst environmental scenario among the thermal processes. Given 1 MJ as functional unit, the avoid burdens allocated to the production of the methane injected into the grid are the same for all the scenarios analyzed and the aspects that prevail on the results are the avoided burdens allocated to the electricity production and metal recovery. Given a fixed amount of methane, different yields in methane production (as reported in Table 1) determine different amounts of MSW treated in the different processes. For 1 MJ of upgraded methane, the smallest amount is treated in the advanced thermal treatment process, 0.2 kg (as the yield in methane of this process is the highest); lower avoided burdens (compared to the avoided burden of scenarios 1-3) are, therefore, allocated to the metal's recovery and to the production of electricity from the off gas in scenario 1. The amount of waste treated in scenario 1, 3 is higher-2.8 kg and 1.6 kg, respectively. This results in higher avoided burdens allocated to the electricity recovery from the incineration of residual fractions in scenarios 1-3 and also in higher avoided burden allocated to the recovery of metal in scenario 1.

The other indicators do not show an inversion in the results when 1 MJ of methane is considered as functional unit instead of 1 kg of MSW. This is because the avoided burdens allocated to the recovery of methane, electricity and metal are balanced and do not change the relative effect when the functional unit is changed.

Those results demonstrate how the choice of the functional unit is a key point of a LCA analysis as this may change the trend of the results.

**4.3. UK future energy scenarios of electricity and natural gas mix**

The marginal energy supply (in particular electricity supply), is reported to strongly affect the results of LCA analysis (Kløverpris et al., 2008; Moora and Lahtvee, 2009) and hence, a study of the environmental burden of the scenarios analysed have been performed according to different energy technologies for indirect and avoided activities.

The UK energy mixes (electricity mix and natural gas mix) are evolving towards renewables. National Grid (2014) has foreseen possible future energy scenarios for the UK and has undertaken a detailed analysis to 2035 for each scenario. Four scenarios have been identified by national grid: i) gone green; ii) slow progression; iii) no progression; iv) low carbon life (see supplementary data for further explanation on these scenarios). According to these four scenarios, National Grid (2014) reports the mix of technologies used in the UK to produce electricity and natural gas each year till 2035 (see supplementary data). The environmental burdens of technology mix for these different energy scenarios, according to the data reported by National Grid (2014), have been modelled using Gabi database (Thinkstep, 2015).

The aim of this analysis is to compare scenarios 1, 3 and 5 between 2014 and 2035 in the UK, according to the developing energy (both electricity and gas) mix. Therefore, the evolution in time of the environmental burdens of these processes have been calculated according to the predictions of National Grid (2014) -different energy mixes have been accounted for the energy requirements and avoided burdens for scenarios 1, 3 and 5. The modelling has been performed for the two different functional units, 1 kg of MSW treated and 1 MJ of methane produced.

In the first instance, only future electricity mix scenarios have been included while both electricity and natural gas future mixes have been included in a second time. The two cases do not show significantly different results, highlighting how a change in the electricity technology mix determines a higher variation of the results than a change of the natural gas technology mix. Only the coupled results regarding a change in natural gas mix and electricity mix are reported.

Figure 7 shows the GWPs of scenarios 1, 3, and 5 till 2035 for the two opposite possibilities analysed by National Grid (gone green and no progression, the other scenarios are reported in the supplementary information), per 1 kg of MSW as functional unit. The increase of the share of cleaner electricity sources in the energy mixes determines an increase of the GWP for scenario 1 and 3. This is due to lower avoided burdens allocated to the production of electricity and hence higher total environmental burdens. On the another hand, scenario 5 decreases its environmental burden because of a lower influence of the electricity mix and higher environmental burdens allocated to the production of methane (the natural gas mix increases its environmental burden because of a higher use of LNG and shale gas). The same trend is depicted for all scenarios predicted by National Grid but the GWPs of scenarios 1, 3 and 5 converge most closely in the gone green than in the no progression scenario. High economic growth and support to sustainability determines these results. For all scenarios, from the year 2020-2021 the GWPs of all three processes become almost parallel, slowly converging toward the centre. The inversion of the results (between scenarios 5, 1 and 3) is not seen before 2035. The GWP of the electricity grid which would determine an inversion of the results is calculated to be 0.1 kg of $CO_2$ Eq. per kwh of electricity. This can be attained, for example, with a strong increase of the nuclear power in the grid mix, to greater than a 40% share. When the inversion of the results is attained, the GWP impact of producing methane from MSW would be less than the GWP of producing electricity.

Given 1 kg of MSW as functional unit, if the government policies prioritise sustainability within an increased economic growth, the evolving energy mixes determine a change in the environmental burden of the processes analysed.

Figure 7 also shows the GWP of the technologies analysed till 2035 assuming 1 MJ of methane as functional unit. In this case, the results for the GWP of S.1, S.3 and S.5 for the no progression and gone green scenarios show no change till 2035. This is because when using 1 MJ of methane as functional unit, the main contribution to the GWPS for the three alternatives is the avoided burden allocated to methane. Fixing 1MJ of methane produced, it means the same avoided burdens for methane production are allocated to all three technologies; the avoided burdens allocated to the electricity have a minor environmental impact on the total score of the results and therefore no significant variation of the results is shown (the results for the other cases are in the supplementary information).

However, the key outcome from this analysis is to show that over the next 20-30 years the production of renewable methane is preferable to renewable electricity, no matter which approach is taken in the analysis.

**4.4. Hot spot analysis of the Anaerobic Digestion processes**

To better analyse the implications of performing the AD on centrally or source separated organic waste, a hot spot analysis of the AD for the two cases is also performed. In this assessment, all the processes upstream of the biodegradable waste pre-treatment are not included, as the focus is only on the differences between the two AD processes (see Figures 3 and 4).

Results in Figure 8 and 9 are reported for 1 kg of MSW.

- *Pre-treatment and digestion* (Figure 8). The pre-treatments and digestion sections of both types of AD determine a positive contribution to all the indicators also because no avoided burdens are allocated to them. In both cases, this section mainly influences the indicators that strongly depend on the electricity consumption (ADP, AP, GWP) because the main environmental burdens are determined by indirect activities. For example, the AP of both processes is mainly due to the electricity consumptions. Conversely, the GWP is also due to the direct methane slips from the digesters accounted in the model. Pre-treatment and digester of the two types of AD are shown to have the same environmental impacts because the correlations to calculate the electricity requirements in the model are based on the amount of biodegradable waste in input (assumed to be the same in the two cases).
- *Upgrading.* Both upgrading processes show a highly negative ADP (Figure 8) (in both cases the negative value offsets the positive contributions) thanks to the avoided burdens allocated to the methane injected into the grid. However, the avoided ADP allocated to the AD of source separated waste is 83% lower than the ADP allocated to the AD of centrally separated

waste (this is due to the difference in methane yield, see Table 1). The other indicators do not show any negative impact allocated to the upgrading processes because the positive burdens due to the energy consumptions offset the negative values. The upgrading of the AD of source separated waste shows an AP 85% higher than that of an equivalent process operating on centrally separated waste: this is due to the higher yield in methane that determines also the higher energy consumption.

The burdens allocated to the digestate use are always shown to be positive (except for the FAETP of the source separated process).

- *Digestate use – source separated waste*. In the AD model of source separated waste, part of the nutrient content of the digestate is assumed to be lost after the spreading of the organic fertilizer on the ground. The avoided burdens of the digestate use are calculated as the difference of the positive burdens due to the application of the organic fertilizer to the soils (emissions due to the leaching, evaporation, run off, etc.) and the avoided burdens allocated to the substitution of the chemical fertilizers. Leaching of N into the soils, evaporation and run off constitute heavily polluting emission of nutrients to environment and, for example, this is the main driver for the EP. For this indicator, the emissions of the organic fertilizer after spreading, are higher than the avoided burden allocated to the substitution of chemical fertilizers. The emissions occur also in the case where chemical fertilizers are used but in the LCA model the difference between the emission due to the organic fertilizer and the chemical fertilizer are included. The opposite result is shown for the FAETP; the avoided burdens allocated to chemical fertilizers offset the impact due to the emissions to environment. Hence, for this indicator the weight of the substitution of chemical fertiliser is higher.
- *Digestate use* - *centrally separated waste.* In the case of AD applied to centrally separated waste the digestate is assumed to be co-incinerated with other waste. A mass balance indicates that the mass of nutrients in input to the incineration process needs to be found in the outputs as either emission to air or as ash. Therefore, those nutrients reach the environment and equally contribute to the EP. The same explanation can be applied to the ODP whereas the GWP is mainly due to the incineration of the fibres.

- *GWP- direct, indirect and avoided contributions.* Figure 9 shows the GWP of the two AD processes (from source separated and centrally separated waste, not including the processes that are upstream the biodegradable waste pre-treatment) and specify the contributions coming from direct, indirect and avoided activities. The process of AD from source separated waste determines a lower impact than the process of AD from centrally separated waste because of the higher yield in methane: 1.04E-1 and 1.12E-1 kg of $CO_2$ Eq., respectively. However, the direct burden contributes around 47% to the total GWP, whereas for the process of AD from centrally separated, this percentage decreases to the 24%. This disparity in the results is due to higher methane yield and therefore higher direct emission of carbon dioxide from the upgrading. The total avoided burdens allocated to the AD of source separated waste are smaller than the avoided burdens allocated to the other process even if the yield in methane of the latter is lower: -1.94E-3 and -2.56E-3 kg of $CO_2$ Eq., respectively. The reason for this is that the avoided burdens of the AD from source separated waste does not only include the production of methane but also the substitution of chemical fertilizer and the emissions due to the evaporation, leaching and run off of part of the digestate nutrients. The higher indirect burdens of the AD of centrally separated waste are due to the higher parasitic loads allocated to the pre-treatment and digestion.

The electricity consumption for digestate dewatering in the AD process from source separated waste determines a negligible environmental burden to all indicators.

## 5. Conclusions

In this work we have analysed the environmental performances of conventional and advanced treatment technologies of MSW focusing on the Bio-SNG production. Five scenarios have been identified, the main processes being: Mechanical Treatment associated with Anaerobic Digestion of centrally separated organic waste and landfill/incineration of the residual waste; source separation of food waste with landfill/incineration of residual waste; and a dual stage advanced thermal treatment process. The model for the inventory has been built based on literature and industry data and a complete environmental analysis have been performed. Furthermore, for the 5 scenarios analysed, two different approaches were considered. One was looking at the best environmental technology for treatment of waste, the other focused instead on the renewable methane production. This was reflected on the choice of the functional unit, 1 kg of MSW and 1 MJ of methane produced, respectively for the two approaches. A unique trend in all the results cannot be identified but each process performs differently depending on the indicators analyzed. Avoided burdens for energy production and direct emissions play the major role on the environmental burdens.

When the problem of waste management is approached, for the GWP, it is currently better to produce electricity from waste over bio-methane/Bio-SNG (as a result of the current UK energy mix) but this is due to change for future energy scenarios. In fact, this work has also analysed the projection of GWP for the processes studied till 2035 accounting for future energy scenarios. Over this period of time, it is predicted that there will be a strong decrease in carbon emissions for the electricity mix compared to the natural gas mix. In the context of waste to energy, this will enhance those technologies that produce renewable methane at high efficiency compared to converting waste for electricity production.

However, the functional unit was shown to be a key parameter for the overall trend of the results. In fact, when the problem of renewable energy production was tackled (functional unit 1 MJ of methane), the current GWP showed that the best option is the treatment of MSW in a dual stage advanced thermal treatment as a result of a higher efficiency in methane production. This trend is not due to change in the next future.

A hot spot analysis was performed for the AD processes from source separated and centrally separated waste. The pre-treatment and digestion processes determine a positive contribution to all the indicators, showing that no avoided burdens are allocated to them; the main environmental burdens of the pre-treatment and digestion are determined by their energy consumptions. However, the GWP is mainly due to the methane slips from the digester. ADP is the only indicator showing avoided burdens allocated to the two upgrading processes. For the digestate use of AD of source separated waste, the majority of the indicators are shown to be positive (mainly the EP, ODP and AP). This is because once on the soil, the burden due to the run-off, evaporation and leaching of N compounds from the organic fertilizer are higher than the avoided burden allocated to the substitution of chemical fertilizers. Those emissions strongly limit the environmental performance of this process when compared to the advanced thermal treatment of waste.

The outcome of this study may be useful to policy makers to inform decisions to improve and sustain future policies for waste management and energy production.

| Scenario | kg of MSW treated/MJ of methane produced |
|---|---|
| **Scenario1-2** | 1.69 |
| **Scenario 3-4** | 0.92 |
| **Scenario 5** | 0.204 |

**Table 1. Yield in biogas production of the scenarios investigated.**

| | | **Modelled parameter** | **Value** | **Reference** |
|---|---|---|---|---|
| ***AD of S.1, S.2*** | **Pre-treatment and digester** | Continuous, single-stage, mixed tank mesophilic reactor operating at a temperature of 35 ˚C | - | (Berglund and Börjesson, 2006; Evangelisti et al., 2014a; Monnet, 2003; Severn Wye Energy Agency, 2009) |
| | | Biogas yield | 0.079 $Nm^3$/kg of centrally separated organic fraction | (Monson et al., 2007) |
| | | Digester methane losses | 3% | (Berglund and Börjesson, 2006; Boldrin et al., 2011; Dalemo et al., 1997; Fruergaard and Astrup, 2011) |
| | **Water and acids removal** | Reaction of $H_2S$ with a catalytic bed of ZnO | - | (Hagen and Polman, 2001; Persson, 2003) |
| | | Water adsorbed on silica gel | - | (Hagen and Polman, 2001; Persson et al., 2006) |
| | **Biogas up-grading by PSA** | Electricity consumption | 0.8-0.88 kWh/$Nm^3$ | (Persson, 2003; Persson et al., 2006) |
| | | Methane losses | 3% | (Patterson et al., 2011; Persson et al., 2006; Petersson, A. Wellinger, 2009) |
| | **Digestate disposal** | To incineration | - | (Swiss Centre for Life Cycle Inventories, 2014) |
| ***AD of S.3, S.4*** | **Pre-treatment and digester** | Biogas yield | 0.14 $Nm^3$/kg of source separated organic fraction | (Banks et al., 2011; Evangelisti et al., 2014a; Møller et al., 2009; Robertson et al., 2010) |
| | **Digestate disposal** | Fibres in the digestate | 20% | (Wrap, 2012) |
| | | Liquor in the digestate | 80% | (Wrap, 2012) |
| | | N of the liquor readily available to crops | 80% | (Wrap, 2011) |
| | | $P_2O_5$ of the liquor readily available to crops | 100% | (Wrap, 2011) |
| | | $K_2O$ of the liquor readily available to crops | 100% | (Wrap, 2011) |
| | | Chemical fertilizer substituted by N | ammonium sulphate | (Defra, 2010) |
| | | Chemical fertilizer substituted by $P_2O_5$ | superphosphate | (Defra, 2010) |
| | | Chemical fertilizer substituted by $K_2O$ | potassium chloride | (Defra, 2010) |
| | | Nutrients dispersed to environment | - | (Boldrin et al., 2011; Bruun et al., 2006; Evangelisti et al., 2014b; Møller et al., 2009) |
| **S.5** | | Oxygen requirements | Average EU cryogenic oxygen production | (Thinkstep, 2015) |
| | | Vitrified slag: system expansion | Primary aggregates crushed rock | (Korre and Durucan, 2009; Mankelow et al., 2011) |
| | | APC residue treatment | - | (Swiss Centre for Life Cycle Inventories, 2014; Thinkstep, 2015) |
| | | Water disposal | - | (Thinkstep, 2015) |
| | | Chemical requirements | - | (Swiss Centre for Life Cycle Inventories, 2014; Thinkstep, 2015) |
| | | Direct and avoided burdens | - | Supplied by industrial developers |

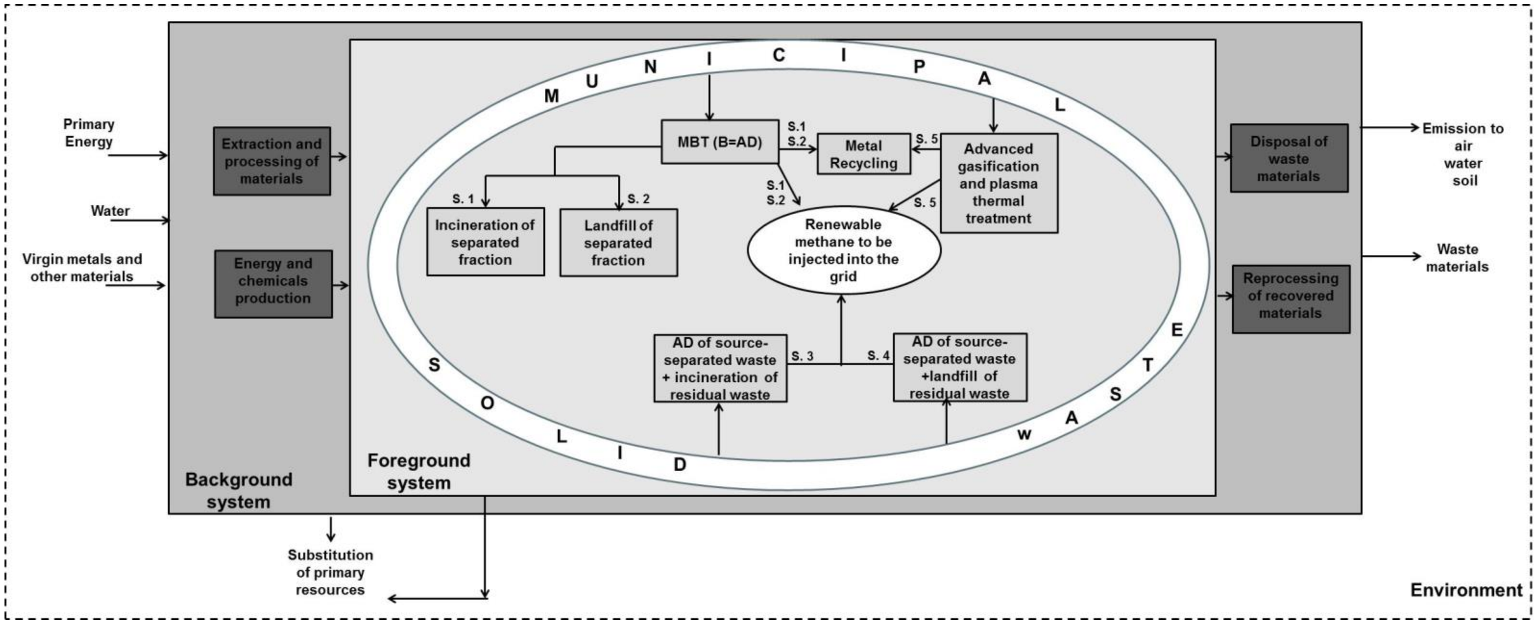
**Table 2. Key inventory data**

| MSW Composition | %wt |
|---|---|
| Paper and Card | 22.7 |
| Wood | 3.7 |
| Metals | 4.3 |
| Glass | 6.6 |
| WEEE | 2.2 |
| Textiles | 2.8 |
| Plastics | 10 |
| Organic Fines | 35.3 |
| Inert/Aggregates/Soils | 5.3 |
| Misc. Comb | 7.1 |
| NCV MJ/kg | 9 |

**Table 3. Residual waste composition** (Evangelisti et al., 2015)**.**

| Scenarios | Emissions to air [kg] | | Emissions to water [kg[ |
|---|---|---|---|
| | Ammonia | Nitrogen Oxides | Total Nitrogen |
| **Scenario 1** | 1.34E-05 | -4.41E-05 | -1.83E-09 |
| **Scenario 3** | 3.95E-05 | 2.10E-05 | -1.24E-09 |
| **Scenario 5** | 6.93E-06 | 2.61E-04 | 3.22E-09 |

**Table 4. Emissions of ammonia and nitrogen oxides to air and of total nitrogen to fresh water. Data are reported as per 1 kg of waste as functional unit.**



Primary Energy
Water
Virgin metals and other materials
Extraction and processing of materials
Energy and chemicals production
Background system
Foreground system
M U N I C I P A L
S O L I D
W A S T E
MBT (B=AD)
S. 1
S. 2
Incineration of separated fraction
Landfill of separated fraction
S.1
S.2
Metal Recycling
S. 5
Advanced gasification and plasma thermal treatment
S.1
S.2
S. 5
Renewable methane to be injected into the grid
AD of source-separated waste + incineration of residual waste
S. 3
S. 4
AD of source-separated waste +landfill of residual waste
Disposal of waste materials
Reprocessing of recovered materials
Emission to air water soil
Waste materials
Substitution of primary resources
Environment

**Figure 1. System boundary**

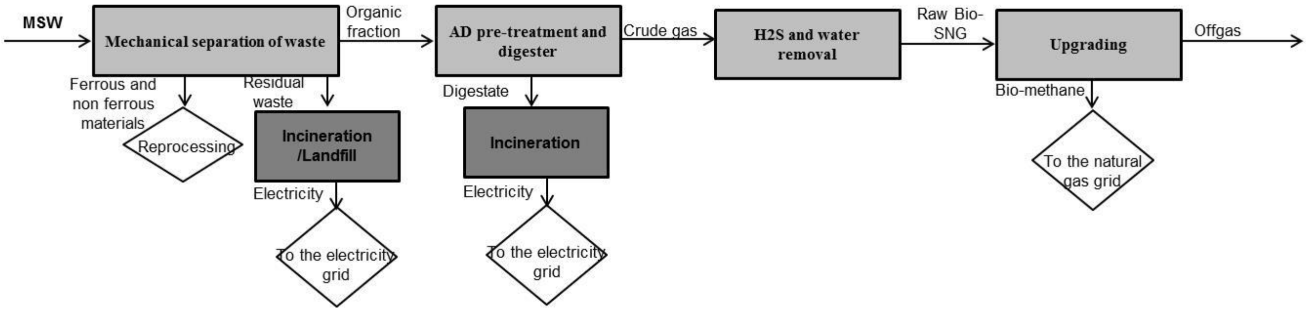



**Figure 2. High level diagram of the anaerobic digestion process of centrally separated organic waste (S.1, S.2).**

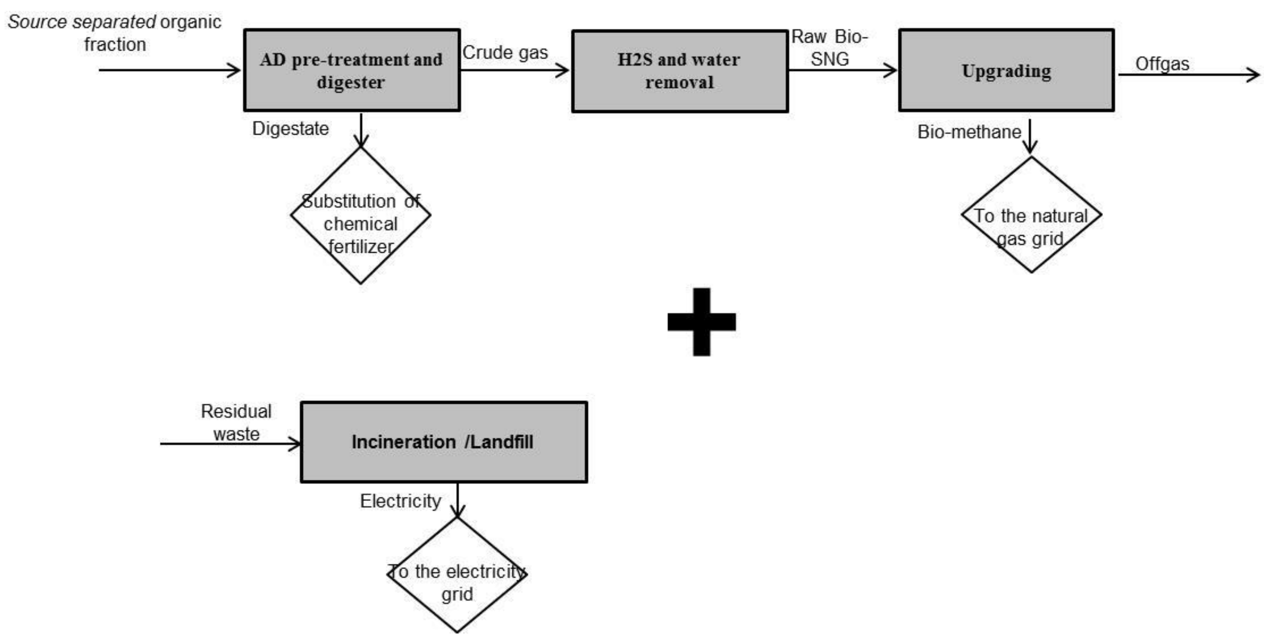



**Figure 3. High level diagram of the anaerobic digestion process of source separated organic waste (S.3, S.4).**

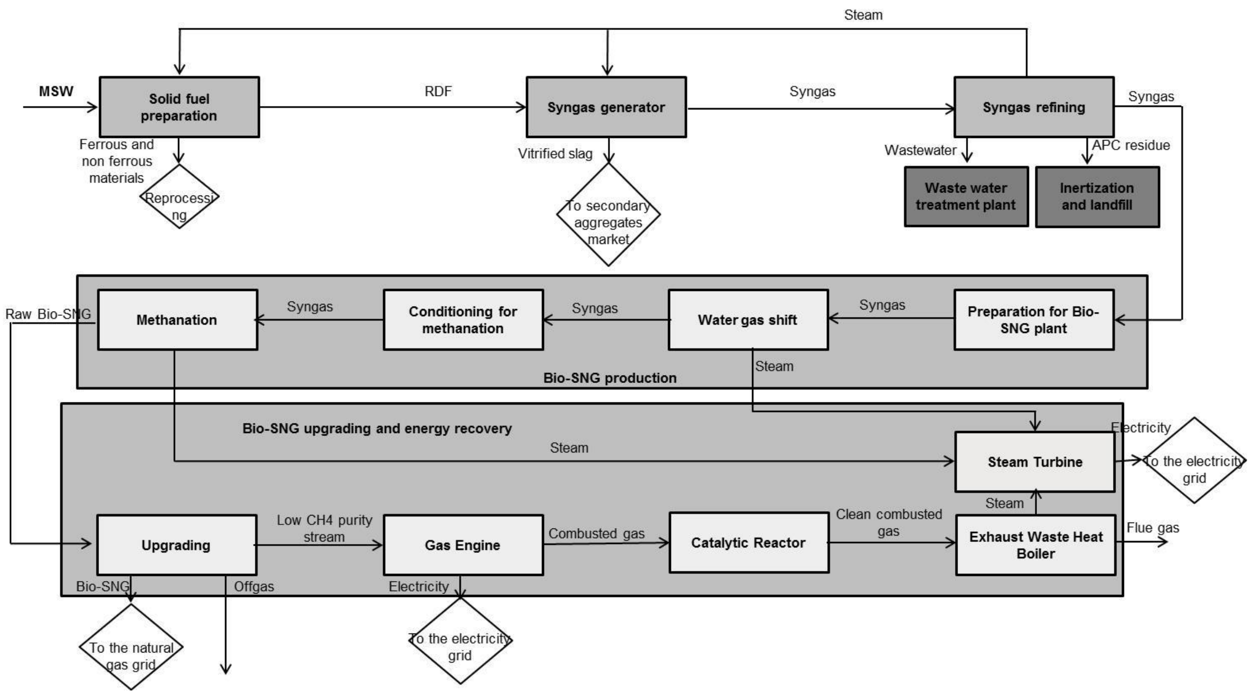



**Figure 4. High level diagram of the gasification and plasma technology producing Bio-SNG from MSW (S.5).**

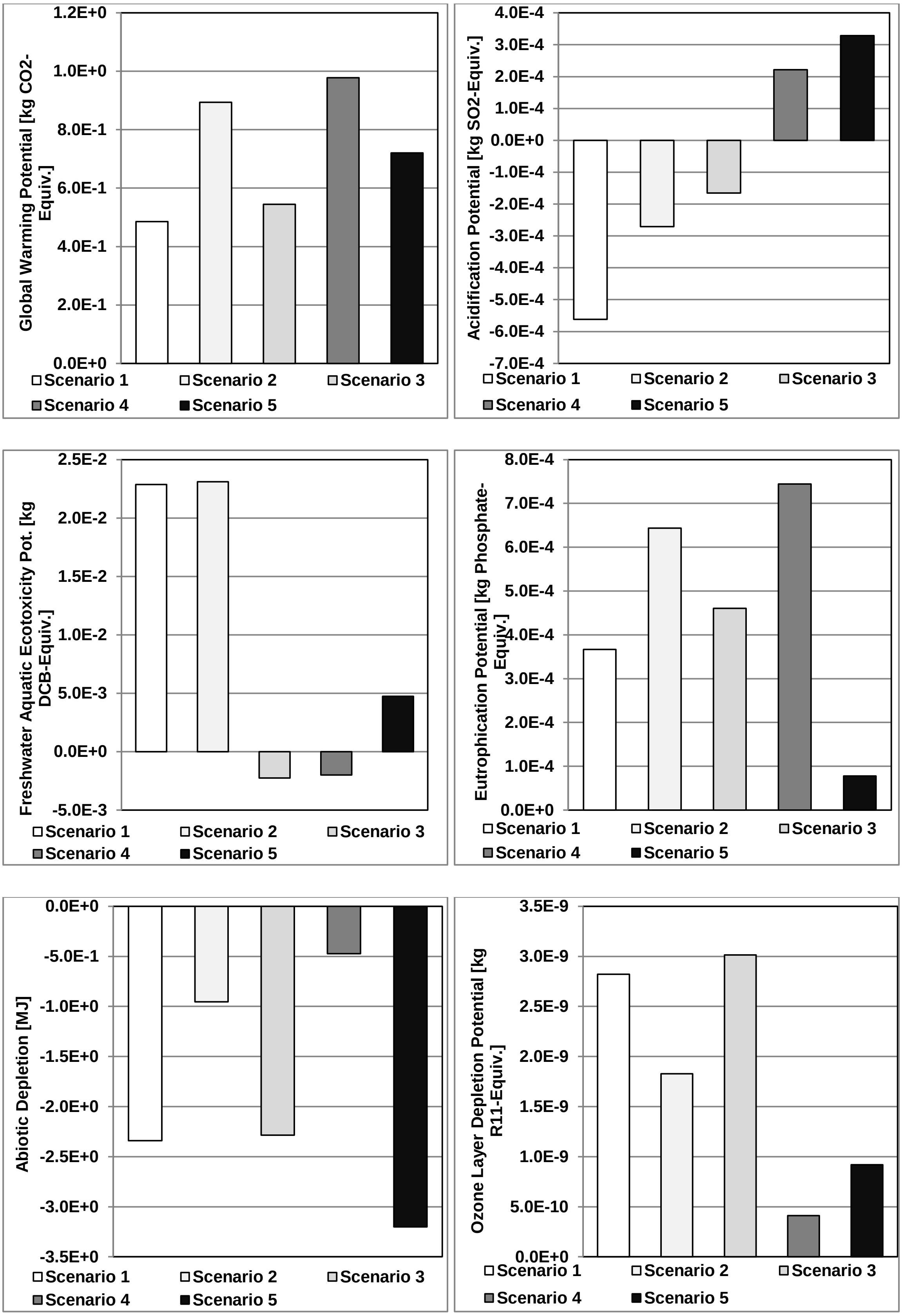



**Figure 5. Environmental impacts of the scenarios analysed. Results are reported per 1 kg of waste as functional unit.**

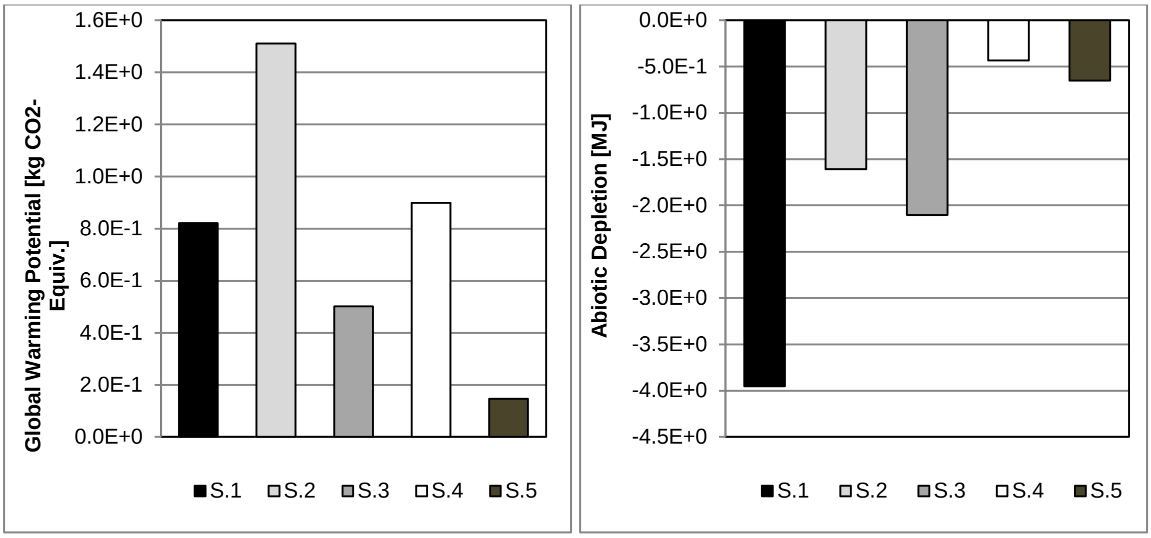



**Figure 6. Environmental impacts of the scenarios analysed. Results are reported per 1 MJ of upgraded methane.**

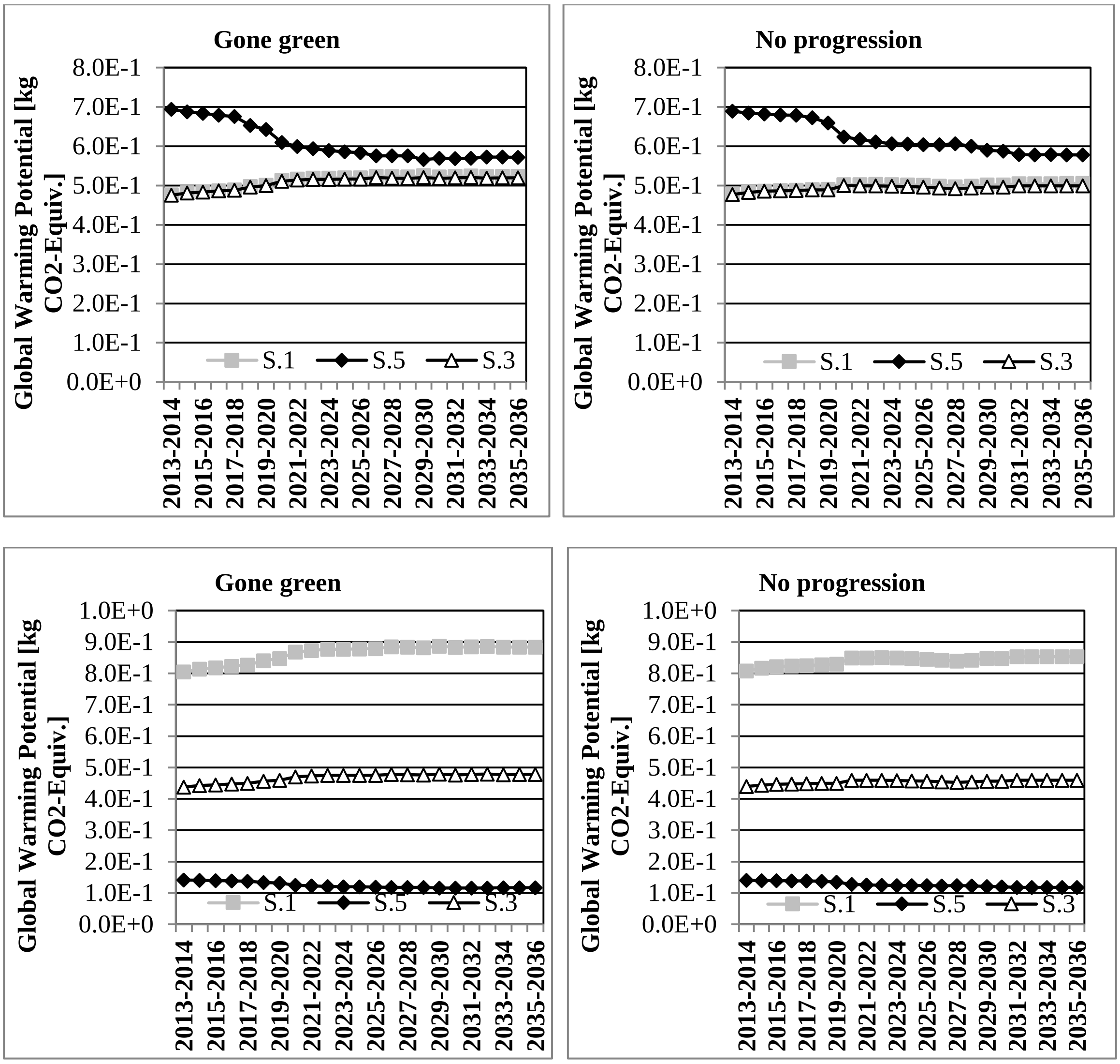



**Figure 7. GWPs of S.1, S.3 and S.5 for future foreseen electricity and natural gas UK mix according to the a) gone green scenario (1 kg of MSW as functional unit); b) no progression scenario (1 kg of MSW as functional unit); c) gone green scenario (1 MJ of upgraded methane as functional unit) no progression scenario (1 MJ of upgraded methane as functional unit). The slow progression and no carbon life scenarios are reported in the supplementary material.**

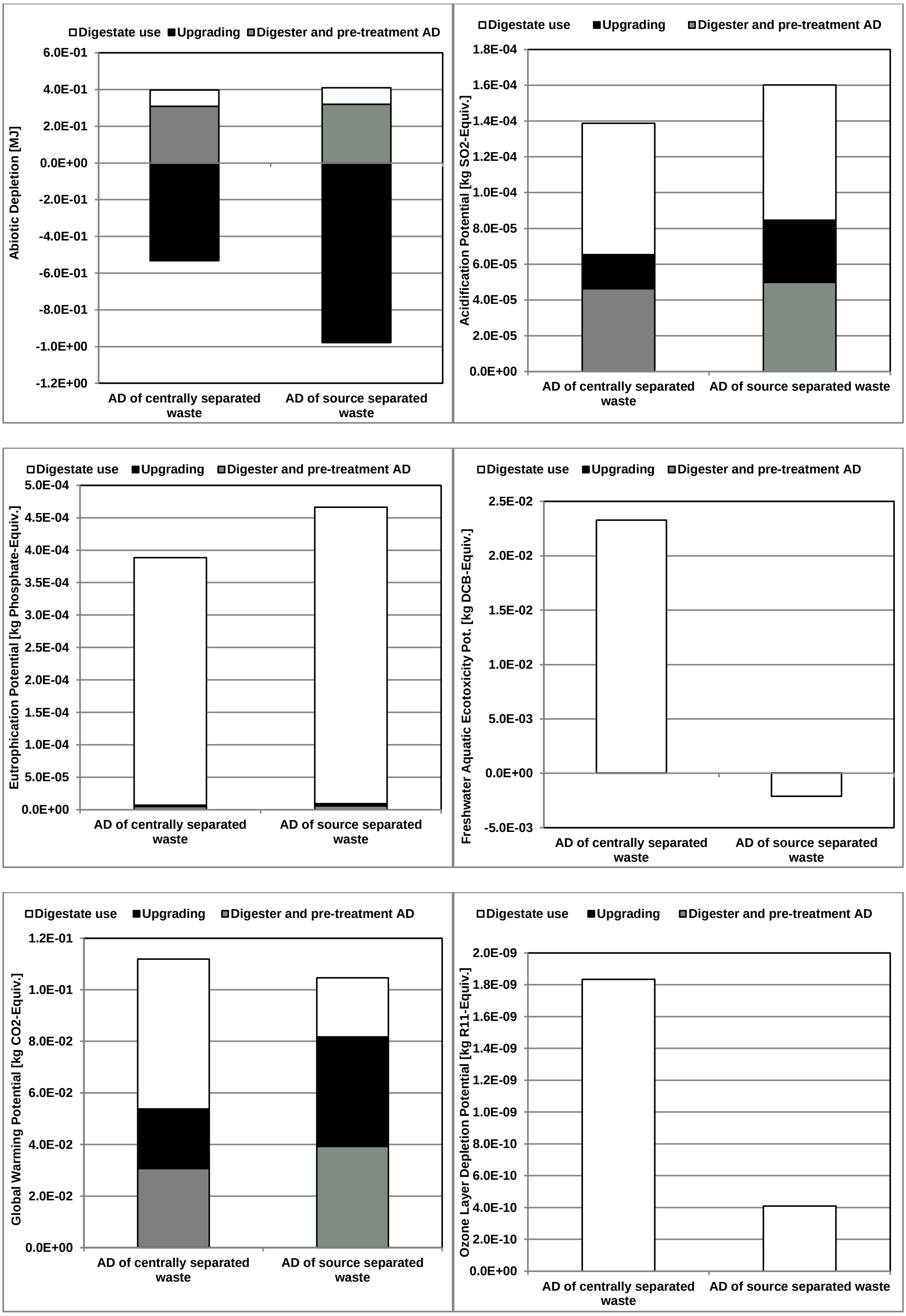



**Figure 8. Hot spot analysis of the AD processes from centrally separated waste and source separated waste. Results are reported per1 kg of waste as functional unit. a) ADP; b) AP; c) EP; d) FAETP; e) GWP; f) ODP. Results are reported per 1kg of waste as functional unit.**

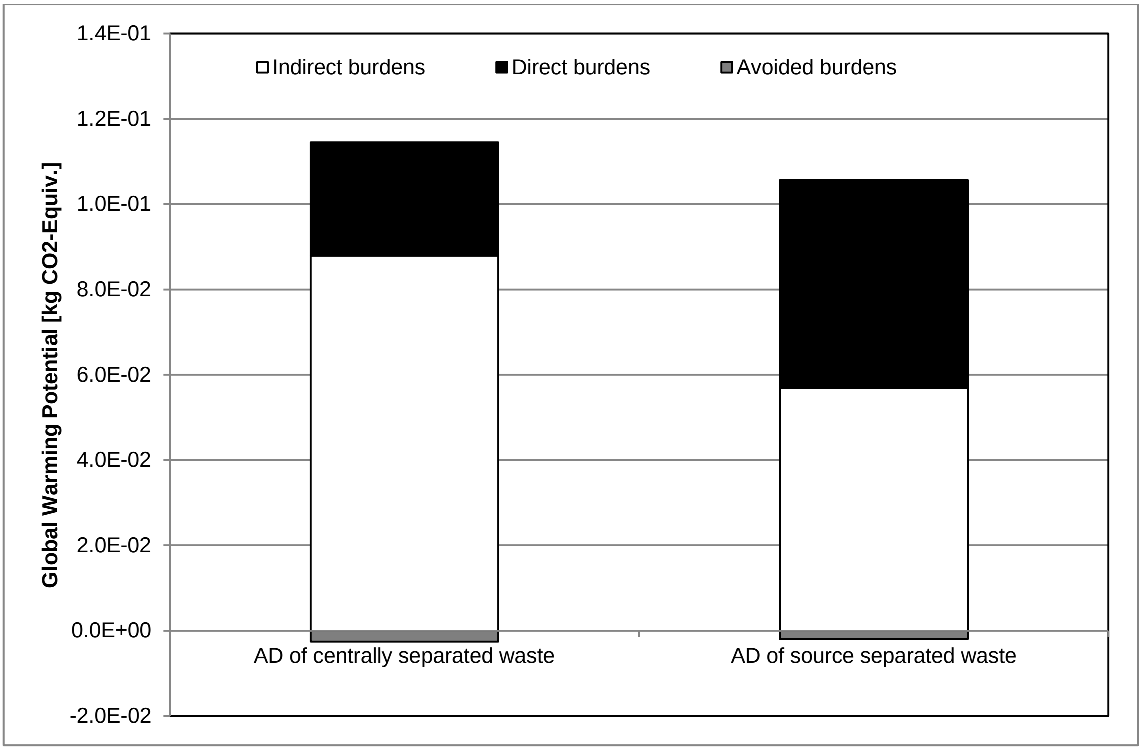



**Figure 9. GWP of the AD processes from centrally separated waste and source separated waste. Indirect, direct and avoided burdens are identified. Results are reported per 1kg of waste as functional unit.**

## Reference


Advanced Plasma Power, 2015. Process Overview [WWW Document]. URL http://www.advancedplasmapower.com/solutions/process-overview/ (accessed 2.25.15).

Appl, M., 2000. Ammonia, 2. Production Processes. Ullmann's Encycl. Ind. Chem.

Archer, E., Klein, A., Whiting, K., 2005. Mechanical-Biological-treatment: a guide for decision makers, processes, policies and markets [WWW Document]. URL http://www.surreycc.gov.uk/__data/assets/pdf_file/0020/167501/11-Juniper-MBT-Markets-for-Outputs.pdf

Arena, U., Mastellone, M.., Perugini, F., 2003. The environmental performance of alternative solid waste management options: a life cycle assessment study. Chem. Eng. J. 96, 207–222. doi:10.1016/j.cej.2003.08.019

Astrup, T., Møller, J., Fruergaard, T., 2009. Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 789–99. doi:10.1177/0734242X09343774

Baddeley, A., Ballinger, A., Hogg, D., 2010. Comparative Life-cycle Assessment INEOS Bio Ltd Seal Sands Waste to Biofuel Initial Plant [WWW Document]. URL http://www.ineos.com/global/bio/she/rs398_ineos bio life-cycle assessment.pdf (accessed 3.10.15).

Banks, C.J., Chesshire, M., Heaven, S., Arnold, R., 2011. Anaerobic digestion of source-segregated domestic food waste: performance assessment by mass and energy balance. Bioresour. Technol. 102, 612–20. doi:10.1016/j.biortech.2010.08.005

Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application. Lund, Sweden, Studentlitteratur.

Berglund, M., Börjesson, P., 2006. Assessment of energy performance in the life-cycle of biogas production. Biomass and Bioenergy 30, 254–266. doi:10.1016/j.biombioe.2005.11.011

Boldrin, A., Neidel, T.L., Damgaard, A., Bhander, G.S., Møller, J., Christensen, T.H., 2011. Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. Waste Manag. 31, 619–30. doi:10.1016/j.wasman.2010.10.025

Boll, W., Hochgesand, G., Higman, C., Supp, E., Kalteier, P., Muller, W., Kriebel, M., Schlichting, H., Tanz, H., 2000. Gas Production, 3. Gas Treating. Ullmann's Encycl. Ind. Chem.

Bruun, S., Hansen, T.L., Christensen, T.H., Magid, J., Jensen, L.S., 2006. Application of processed organic municipal solid waste on agricultural land – a scenario analysis. Environ. Model. Assess. 11, 251–265. doi:10.1007/s10666-005-9028-0

Buttol, P., Masoni, P., Bonoli, A., Goldoni, S., Belladonna, V., Cavazzuti, C., 2007. LCA of integrated MSW management systems: case study of the Bologna District. Waste Manag. 27, 1059–70. doi:10.1016/j.wasman.2007.02.010

Chapman, C.D., Faraz, A., Taylor, R.J., 2014. Utilisation of oxygen for enhanced gasification performance. Proc. ICE - Waste Resour. Manag. 167, 15–24. doi:10.1680/warm.13.00019

Clift, R., 2013. System Approaches: Life Cycle Assessment and Industrial Ecology, in: Pollution: Causes, Effects and Control. R.M. Harrison Royal Society of Chemistry, London.

Clift, R., 2006. Sustainable development and its implications for chemical engineering. Chem. Eng. Sci. 61, 4179–4187. doi:10.1016/j.ces.2005.10.017

Clift, R., Doig, A., Finnveden, G., 2000. THE APPLICATION OF LIFE CYCLE ASSESSMENT TO INTEGRATED SOLID WASTE MANAGEMENT. Process Saf. Environ. Prot. 78, 279–287.

Communities and local Government, 2011. Planning policy statement 10-Planning for sustainable waste management [WWW Document]. URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/11443/1876202.pdf

Consonni, S., Giugliano, M., Grosso, M., 2005a. Alternative strategies for energy recovery from municipal solid waste Part B: Emission and cost estimates. Waste Manag. 25, 137–48. doi:10.1016/j.wasman.2004.09.006

Consonni, S., Giugliano, M., Grosso, M., 2005b. Alternative strategies for energy recovery from municipal solid waste Part A: Mass and energy balances. Waste Manag. 25, 123–35. doi:10.1016/j.wasman.2004.09.007

Dalemo, M., Sonesson, U., Björklund, A., Mingarini, K., Frostell, B., Jönsson, H., Nybrant, T., Sundqvist, J.-O., Thyselius, L., 1997. ORWARE – A simulation model for organic waste handling systems. Part 1: Model description. Resour. Conserv. Recycl. 21, 17–37. doi:10.1016/S0921-3449(97)00020-7

DECC, 2011. Renewable Heat Incentives [WWW Document]. URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48041/1387-renewable-heat-incentive.pdf (accessed 3.10.15).

Defra, 2013. UK renewable energy road map update [WWW Document]. URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255182/UK_Renewable_Energy_Roadmap_-_5_November_-_FINAL_DOCUMENT_FOR_PUBLICATIO___.pdf (accessed 3.10.15).

Defra, 2011. Guidance on applying the waste hierarchy.

Defra, 2010. RB209 Fertiliser Manual [WWW Document]. URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69469/rb209-fertiliser-manual-110412.pdf (accessed 2.24.15).

den Boer, J., den Boer, E., Jager, J., 2007. LCA-IWM: a decision support tool for sustainability assessment of waste management systems. Waste Manag. 27, 1032–45. doi:10.1016/j.wasman.2007.02.022

Ekvall, T., Finnveden, G., 2001. Allocation in ISO 14041—a critical review. J. Clean. Prod. 9, 197–208. doi:10.1016/S0959-6526(00)00052-4

Eriksson, O., Finnveden, G., Ekvall, T., Björklund, A., 2007. Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion. Energy Policy 35, 1346–1362. doi:10.1016/j.enpol.2006.04.005

Esmaeil, H.R., Yusoff, S., Nouri, J., Asadi, J., 2012. Life cycle assessment of biological-mechanical treatment in solid waste management. Sci. Res. Essays 7, 553–559.

European Commission, 2009. Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

European Commission, 2003. Integrated Product Policy, Building on Enviornmnental Life-Cycle Thinking [WWW Document]. URL http://center.sustainability.duke.edu/sites/default/files/documents/integratedproductpolicy.pdf (accessed 3.4.15).

European Council, 2014. 2014 – 2030 framework for climate and energy policies [WWW Document]. URL http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf

Evangelisti, S., Lettieri, P., Borello, D., Clift, R., 2014a. Life cycle assessment of energy from waste via anaerobic digestion: a UK case study. Waste Manag. 34, 226–37. doi:10.1016/j.wasman.2013.09.013

Evangelisti, S., Lettieri, P., Clift, R., Borello, D., 2014b. Distributed generation by energy from waste technology: A life cycle perspective. Process Saf. Environ. Prot. doi:10.1016/j.psep.2014.03.008

Evangelisti, S., Tagliaferri, C., Clift, R., Lettieri, P., Taylor, R., Chapman, C., 2015. Life cycle assessment of conventional and two-stage advanced energy-from-waste technologies for municipal solid waste treatment. J. Clean. Prod. 100, 212–223. doi:10.1016/j.jclepro.2015.03.062

Felder, R., Dones, R., 2007. Evaluation of ecological impacts of synthetic natural gas from wood used in current heating and car systems. Biomass and Bioenergy 31, 403–415. doi:10.1016/j.biombioe.2006.08.005

Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA perspective. Waste Manag. 31, 572–82. doi:10.1016/j.wasman.2010.09.009

GSMR, 1996. HEALTH AND SAFETY Gas Safety ( Management ) Regulations 1996.

Guinan, B., Milton, D., Kirkman, R., Kristiansen, T., O'Sullivan, D., 2008. Critical Analysis of the Potential of Mechanical Biological Treatment for Irish Waste Management [WWW Document]. URL http://www.epa.ie/pubs/reports/research/waste/strivereport16.html (accessed 3.10.15).

Guinée, J.B., 2002. Handbook on Life Cycle Assessment, Operational Guide to the ISO Standards, Kluwer Aca. ed.

Hacatoglu, K., McLellan, P.J., Layzell, D.B., 2010. Production of bio-synthetic natural gas in Canada. Environ. Sci. Technol. 44, 2183–8. doi:10.1021/es901561g

Hagen, M., Polman, E., 2001. Adding gas from biomass to the gas grid [WWW Document]. URL http://gasunie.eldoc.ub.rug.nl/FILES/root/2001/2044668/2044668.pdf

Heijungs, R., Guinée, J.B., 2007. Allocation and "what-if" scenarios in life cycle assessment of waste management systems. Waste Manag. 27, 997–1005. doi:10.1016/j.wasman.2007.02.013

HM UK Government, 2009. The UK renewable energy strategy [WWW Document]. URL https://www.gov.uk/government/publications/the-uk-renewable-energy-strategy (accessed 3.10.15).

Hong, R.J., Wang, G.F., Guo, R.Z., Cheng, X., Liu, Q., Zhang, P.J., Qian, G.R., 2006. Life cycle assessment of BMT-based integrated municipal solid waste management: Case study in Pudong, China. Resour. Conserv. Recycl. 49, 129–146. doi:10.1016/j.resconrec.2006.03.007

Hospido, A., Moreira, T., Martín, M., Rigola, M., Feijoo, G., 2005. Environmental Evaluation of Different Treatment Processes for Sludge from Urban Wastewater Treatments: Anaerobic Digestion versus Thermal Processes (10 pp). Int. J. Life Cycle Assess. 10, 336–345. doi:10.1065/lca2005.05.210

Hu, M., Guo, D., Ma, C., Hu, Z., Zhang, B., Xiao, B., Luo, S., Wang, J., 2015. Hydrogen-rich gas production by the gasification of wet MSW (municipal solid waste) coupled with carbon dioxide capture. Energy 90, 857–863. doi:10.1016/j.energy.2015.07.122

ISO 14040, 2006. International Standard, In: Environmental Management – Life Cycle Assessment – Principles and Framework, International Organisation for Standardization, Geneva, Switzerland.

Juraščík, M., Sues, A., Ptasinski, K.J., 2010. Exergy analysis of synthetic natural gas production method from biomass. Energy 35, 880–888. doi:10.1016/j.energy.2009.07.031

Kløverpris, J., Wenzel, H., Nielsen, P.H., 2008. Life cycle inventory modelling of land use induced by crop consumption. Int. J. Life Cycle Assess. 13, 13–21. doi:10.1065/lca2007.10.364

Koók, L., Rózsenberszki, T., Nemestóthy, N., Bélafi-Bakó, K., Bakonyi, P., 2016. Bioelectrochemical treatment of municipal waste liquor in microbial fuel cells for energy valorization. J. Clean. Prod. 112, 4406–4412. doi:10.1016/j.jclepro.2015.06.116

Korre, A., Durucan, S., 2009. Life Cycle Assessment of Aggregates [WWW Document]. URL http://www.wrap.org.uk/sites/files/wrap/EVA025-MIRO Life Cycle Assessment of Aggregates final report.pdf

Lundie, S., Peters, G.M., 2005. Life cycle assessment of food waste management options. J. Clean. Prod. 13, 275–286. doi:10.1016/j.jclepro.2004.02.020

Luterbacher, J.S., Fröling, M., Vogel, F., Maréchal, F., Tester, J.W., 2009. Hydrothermal Gasification of Waste Biomass: Process Design and Life Cycle Asessment. Environ. Sci. Technol. 43, 1578–1583. doi:10.1021/es801532f

Manfredi, S., Pant, R., 2011. Supporting environmentally sound decisions for waste management: A technical guide to Life Cycle Thinking (LCI) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners [WWW Document]. URL http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/22582/1/reqno_jrc65850_lb-na-24916-en-n _pdf_.pdf (accessed 3.4.15).

Mankelow, J.M., Sen, M.A., Wrighton, C.E., Idoine, N., 2011. Collation of the results of the 2009 aggregate minerals survey for England and Wales [WWW Document]. URL https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/6366/1909597.pdf

Mezzullo, W.G., McManus, M.C., Hammond, G.P., 2013. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. Appl. Energy 102, 657–664. doi:10.1016/j.apenergy.2012.08.008

Mohareb, A.K., Warith, M.A., Diaz, R., 2008. Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. Resour. Conserv. Recycl. 52, 1241–1251. doi:10.1016/j.resconrec.2008.06.006

Moller, H., Hansen, J.D., Soresen, C.A.G., 2007. NUTRIENT RECOVERY BY SOLID-LIQUID SEPARATION AND METHANE PRODUCTIVITY OF SOLIDS. Am. Soc. Agric. Biol. Eng. 50, 193–200.

Møller, J., Boldrin, A., Christensen, T.H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 813–24. doi:10.1177/0734242X09344876

Monnet, F., 2003. An Introduction to Anaerobic Digestion of Organic Wastes [WWW Document]. URL http://www.biogasmax.co.uk/media/introanaerobicdigestion__073323000_1011_24042007.pdf

Monson, K.D., Esteves, S.R., Guwy, A.J., Dinsdale, R.., 2007. Anaerobic digestion of biodegradable Municipals wastes A review [WWW Document]. URL http://www.walesadcentre.org.uk/Controls/Document/Docs/Anaerobic Digestion of BMW _compressed_ - A Review _for print_.pdf (accessed 2.24.15).

Montejo, C., Tonini, D., Márquez, M.D.C., Astrup, T.F., 2013. Mechanical-biological treatment: performance and potentials. An LCA of 8 MBT plants including waste characterization. J. Environ. Manage. 128, 661–73. doi:10.1016/j.jenvman.2013.05.063

Moora, H., Lahtvee, V., 2009. ELECTRICITY SCENARIOS FOR THE BALTIC STATES AND MARGINAL ENERGY TECHNOLOGY IN LIFE CYCLE ASSESSMENTS -- A CASE STUDY OF ENERGY PRODUCTION FROM MUNICIPAL WASTE INCINERATION. Oil Shale 26, 331–346.

National Grid, 2014. UK Future Energy Scenarios [WWW Document]. URL http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-scenarios/

Panepinto, D., Tedesco, V., Brizio, E., Genon, G., 2014. Environmental Performances and Energy Efficiency for MSW Gasification Treatment. Waste and Biomass Valorization 6, 123–135. doi:10.1007/s12649-014-9322-7

Patterson, T., Esteves, S., Dinsdale, R., Guwy, A., 2011. Life cycle assessment of biogas infrastructure options on a regional scale. Bioresour. Technol. 102, 7313–23. doi:10.1016/j.biortech.2011.04.063

Persson, M., 2003. Evaluation of upgrading techniques for biogas [WWW Document]. doi:SGC142

Persson, M., Wellinger, A., Rehnlund, B. Rahm, L., Hugosson, B., 2006. Report on technological applicability of existing biogas upgrading processes [WWW Document]. URL http://www.biogasmax.eu/media/report_on_technological_2007__041639600_1025_22052007.pdf (accessed 2.24.15).

Petersson, A. Wellinger, A., 2009. Biogas upgrading technologies- developments and innovations [WWW Document]. URL http://www.iea-biogas.net/files/daten-redaktion/download/publi-task37/upgrading_rz_low_final.pdf (accessed 2.24.15).

Pucker, J., Zwart, R., Jungmeier, G., 2012. Greenhouse gas and energy analysis of substitute natural gas from biomass for space heat. Biomass and Bioenergy 38, 95–101. doi:10.1016/j.biombioe.2011.02.040

Ray, R., Taylor, R., Chapman, C., 2012. The deployment of an advanced gasification technology in the treatment of household and other waste streams. Process Saf. Environ. Prot. 90, 213–220. doi:10.1016/j.psep.2011.06.013

REA, 2011. Energy from waste a guide for decisions-makers [WWW Document]. URL http://www.r-e-a.net/pdf/energy-from-waste-guide-for-decision-makers.pdf (accessed 3.5.15).

Robertson, R., Blanco-Madrigal, E., Arnold, R., 2010. Seventh framework programme theme energy.2009.3.2.2- Biowaste as feedstock for 2nd generation [WWW Document]. URL http://www.valorgas.soton.ac.uk/Deliverables/111129_VALORGAS_241334_D5-1_Final_version.pdf (accessed 2.24.15).

Rózsenberszki, T., Koók, L., Hutvágner, D., Nemestóthy, N., Bélafi-Bakó, K., Bakonyi, P., Kurdi, R., Sarkady, A., 2015. Comparison of Anaerobic Degradation Processes for Bioenergy Generation from Liquid Fraction of Pressed Solid Waste. Waste and Biomass Valorization 6, 465–473. doi:10.1007/s12649-015-9379-y

Severn Wye Energy Agency, 2009. BIOGAS REGIONS An Introduction to Biogas and Anaerobic Digestion A guide for England and Wales [WWW Document]. URL http://www.severnwye.org.uk/downloads/Biogas_Brochure.pdf

Slagstad, H., Brattebø, H., 2012. LCA for household waste management when planning a new urban settlement. Waste Manag. 32, 1482–90. doi:10.1016/j.wasman.2012.03.018

Steubing, B., Zah, R., Ludwig, C., 2011. Life cycle assessment of SNG from wood for heating, electricity, and transportation. Biomass and Bioenergy 35, 2950–2960. doi:10.1016/j.biombioe.2011.03.036

Sues, A., Juraščík, M., Ptasinski, K., 2010. Exergetic evaluation of 5 biowastes-to-biofuels routes via gasification. Energy 35, 996–1007. doi:10.1016/j.energy.2009.06.027

Swiss Centre for Life Cycle Inventories, 2014. Ecoinvent: the life cycle inventory data, Version 3.0. Swiss Centre for Life Cycle Inventories, Duebendorf.

Tan, S.T., Hashim, H., Lim, J.S., Ho, W.S., Lee, C.T., Yan, J., 2014. Energy and emissions benefits of renewable energy derived from municipal solid waste: Analysis of a low carbon scenario in Malaysia. Appl. Energy 136, 797–804. doi:10.1016/j.apenergy.2014.06.003

Taylor, R., Chapman, C., 2012. ADVANCED PLASMA POWER LTD CONVERTING WASTE INTO VALUABLE RESOURCES WITH THE GASPLASMA® PROCESS.

Taylor, R., Ray, R., Chapman, C., 2013. Advanced thermal treatment of auto shredder residue and refuse derived fuel. Fuel 106, 401–409. doi:10.1016/j.fuel.2012.11.071

Thinkstep, 2015. GaBi 6 software-system and databases for life cycle engineering. Stuttgart, Echterdingen (see www.pe-europe.com).

UK Government, 2009. National Renewable Energy Action Plan for the United Kingdom Article 4 of the Renewable Energy Directive 2009/28/EC.

Vitasari, C.R., Jurascik, M., Ptasinski, K.J., 2011. Exergy analysis of biomass-to-synthetic natural gas (SNG) process via indirect gasification of various biomass feedstock. Energy 36, 3825–3837. doi:10.1016/j.energy.2010.09.026

Wrap, 2012. Enhancement and treatment of digestates from anaerobic digestion [WWW Document]. URL http://www.wrap.org.uk/sites/files/wrap/Digestates from Anaerobic Digestion A review of enhancement techniques and novel digestate products_0.pdf

Wrap, 2011. Digestate & Compost in Agriculture, Bulletin 2 – November 2011. Beat rising cost of fertiliser and extreme weather by using digestate and compost [WWW Document]. URL http://www.wrap.org.uk/sites/files/wrap/Bulletin 2 - agronomic benefits_0.pdf

Wrap, 2010. Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials [WWW Document]. URL http://www.wrap.org.uk/sites/files/wrap/PAS110_vis_10.pdf (accessed 2.24.15).

Zhao, W., van der Voet, E., Zhang, Y., Huppes, G., 2009. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: case study of Tianjin, China. Sci. Total Environ. 407, 1517–26. doi:10.1016/j.scitotenv.2008.11.007