Biogas Upgrading: Global Warming Potential of Conventional and Innovative Technologies

Katherine Starr[a], Xavier Gabarrell Durany[b], Gara Villalba Mendez[b], Laura Talens Peiro[c] and Lidia Lombardi[d]

[a] Sostenipra, Department of Chemical Engineering, Xarxa de Referència en Biotechnologia (XRB) de Catalunya, Universitat Autònoma de Barcelona, Bellaterra, Spain, Katherine.starr@uab.cat, CA
[b] Sostenipra, Institute de Ciència i Technologua Ambientals (ICTA), Department of Chemical Engineering, Xarxa de Referència en Biotechnologia (XRB) de Catalunya, Universitat Autònoma de Barcelona, Bellaterra, Spain, Xavier.gabarrell@uab.cat, gara.villalba@uab.cat,
[c] INSEAD - Campus Europe, Fontainebleau, France, laura.talenspeiro@insead.edu
[d] Dipartimento di Energetica, Universita delgi Studi di Firenze, Firenze, Italy lidia.lombardi@unifi.it

Abstract:

Biogas upgrading technologies provides an alternative source of methane and their implementation in waste management systems can help reduce the greenhouse effect. This paper uses a life cycle assessment (LCA) to study eight technologies, six of which are already on the market and the two others are novel technologies that use carbon mineralization in their process in order to not only remove CO2 but also store it. The two technologies are under development in the frame of the UPGAS-LOWCO2 LIFE08/ENV/IT/000429 project (upgas.eu) and include alkaline with regeneration (AwR) and bottom ash upgrading (BABIU). These technologies utilize waste from municipal solid waste incinerators rich in calcium to store CO2 from biogas. Among all conventional technologies, high pressure water scrubbing and chemical scrubbing with amine had the lowest CO2 impacts. The results of the two novel technologies show that BABIU saves 10% more CO2 than AwR. An uncertainty analysis and a material flow analysis showed that the placement of these two novel technologies is an important factor (for CO2 emissions and availability of waste) and therefore they should be located close to a MSWI that produces sufficient waste.

Keywords:

Biogas, Carbon Capture, Carbon Mineralization, Life Cycle Assessment, Sustainability.

1. Introduction

Among the renewables, the biogas industry in the EU is growing, reaching about 8.3 Mtoe in 2009 with more than 6000 biogas plants. The main source is agriculture (52%), then landfills (36%) and sewage plants (12%) [1].

Biogas can be fed with a variety of bio-materials which can be waste or energy crops. Biogas produced in anaerobic digestion plants (AD-plants) or landfill sites is primarily composed of methane (CH_4) and carbon dioxide (CO_2) with smaller amounts of hydrogen sulphide (H_2S) and ammonia (NH_3). Trace amounts of hydrogen (H_2), saturated or halogenated carbohydrates and oxygen (O_2) are occasionally present in the biogas. Usually the gas is saturated with water vapour and may contain dust particles and organic silicon compounds (e.g. siloxanes).

Biogas from anaerobic digestion plants (AD-plants) or landfill sites can be directly used for the production of heat and steam, electricity, vehicle fuels and chemicals. Alternatively, it can be further upgraded to increase the methane concentration, by removing CO_2 and other impurities, in order to be suitable as a substitute for natural gas in the already established distribution grid. This gas can now be regarded as biomethane and is of a quality where it can fed into the natural gas distribution grid or be used as a vehicle fuel. This option is gaining more interest throughout Europe and there are currently several different commercial technologies for reducing the concentration of CO_2 in biogas.

There are four different types of upgrading technologies which removes CO_2 and they include absorption, adsorption, membrane separation and cryogenic separation. For the absorption processes a reagent is used to absorb CO_2. Within absorption one can find high pressure water scrubbing (HPWS) which uses water, chemical scrubbing (AS) which uses an amine based solvent such as diethanolamine (DEA), and organic physical scrubbing (OPS) which uses a commercial blend of polyethylene glycol. Under adsorption CO_2 is normally adsorbed onto a medium such as activated carbon and then removed through changes in pressure, as in the case of pressure swing adsorption (PSA). For membrane separation (MS) a selective membrane is used to separate CO_2 from the biogas. Cryogenic separation (Cry) separates CH_4 and CO_2 through a decrease in temperature which causes a change in the physical state of the gases [2]. The marketed technologies use varying techniques to process the gas but what they do have in common is that they do not permanently store the CO_2, instead it is sent back into the atmosphere or used for industrial purposes if it meets quality requirements [3].

Currently, under the framework of the UPGAS-LOWCO2 LIFE08/ENV/IT/000429 project, there are two novel upgrading technologies under development additionally storing the separated CO_2 through carbon mineralization. These technologies use wastes from municipal solid waste incinerators (MSWI) rich in calcium compounds to fix CO_2 and thus form calcium carbonate ($CaCO_3$). The two technologies that are being developed, and are currently in the pilot plant stage, are alkaline with regeneration (AwR) – developed jointly
"Tor Vergata" in Italy [4,5] - and the bottom ash for biogas upgrading (BABIU) – developed by the University of Natural Resources and Life Sciences in Austria [6,7]. The AwR process, which is a continuous process, absorbs the CO_2 using an alkaline solution of potassium hydroxide (KOH). This solution is regenerated at a rate of 70% when put into contact with air pollution control residues (APC) which is rich in calcium. Once the CO_2 is adsorbed into the APC the biogas (from here referred to as biomethane) is free of impurities. BABIU, which is a batch process, uses a direct solid-gas phase interaction. Biogas is pumped through a column containing bottom ash (BA) rich in calcium, CO_2 is absorbed in the BA and thus the resulting biomethane has a high concentration of CH_4.

In this study the amount of greenhouse gases created and saved by implementing these technologies is analyzed through a life cycle assessment (LCA). Eight technologies that were described above are examined and they include AwR, BABIU, PSA, HPWS, OPS, Cry, MS, and AS. LCA is a useful tool to determine the environmental impact of technologies. While it is often applied to technologies that are on the market, it is often used during the development phase in order to help create a more environmentally sound process [8]. While LCAs have various indicators that can be selected, the Global Warming Potential was chosen as the focus of the study as one of the roles of biogas upgrading technologies could be considered to be reducing CO_2 emissions from anaerobic digesters or landfills.

These results are then compared with a Material Flow Analysis (MFA), which quantifies the flows and stocks of a system, in order to determine the applicability of the novel technologies.

2. Methodology

A life cycle assessment (LCA) was run according to the ISO 14040 [9]. A material flow analysis (MFA) was conducted for the waste flow of Spain as a complement to the LCA.

2.1. Life Cycle Assessment

2.1.1. Goal and Scope

The goal of this study is to determine the global warming potential (GWP) of biogas upgrading technologies. By accounting the GWP, we can identify the process that diverts the highest amount of greenhouse gases from being emitted into the atmosphere.

2.1.2. Functional Unit

The functional unit used for this study is 1 kWh of biomethane upgraded from biogas which is composed of 50% CH_4 and 50% CO_2. This hypothetical composition is applied as it allows one to disregard any prior gas treatment.

2.1.3. System Boundaries

The system boundaries include the electricity used to treat the gas, the production of any reagents used, the amount of biogas that is upgraded, the amount of methane lost during the process either through the treatment (know as methane slip) or lost within the waste gas. Fig. 1 demonstrates the boundaries for the LCA and the uncertainty analysis.

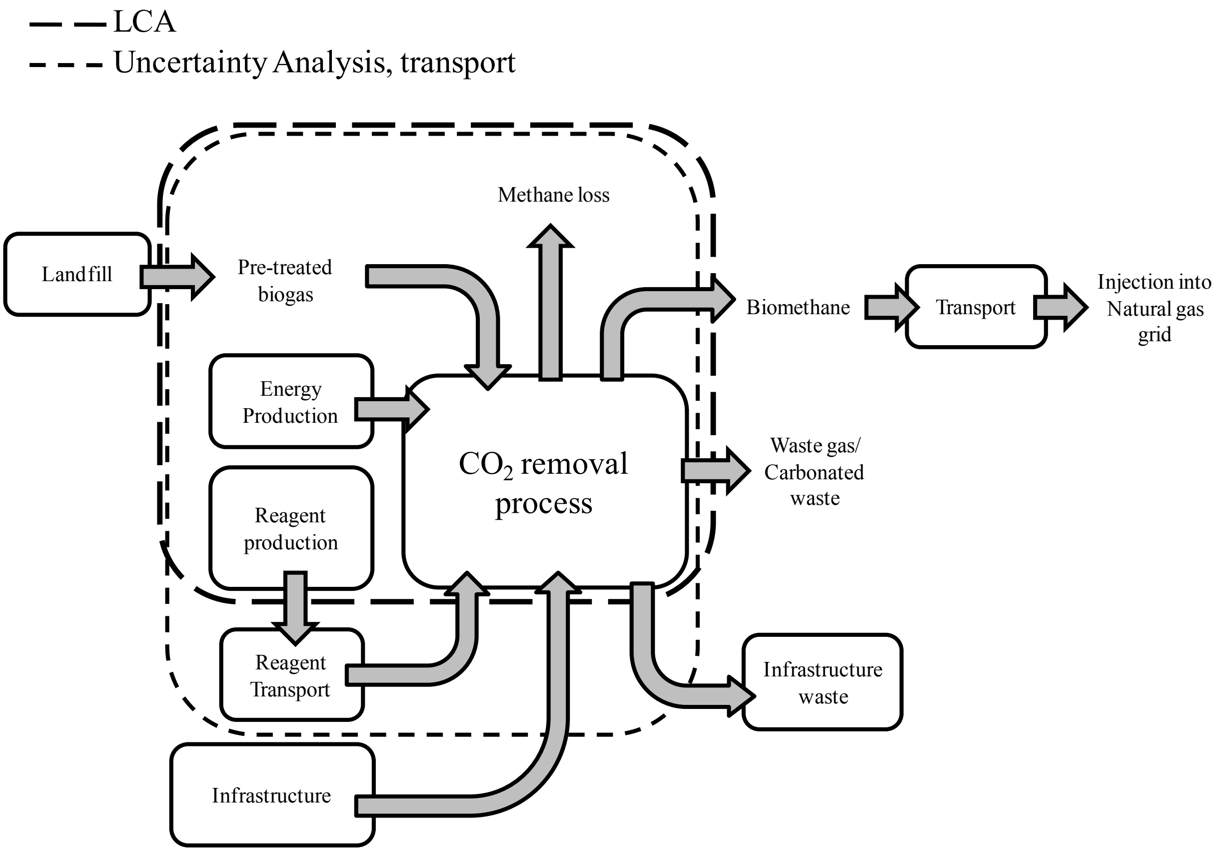

Fig. 1. System boundaries

The processes excluded for the LCA and the uncertainty analyses are the generation of the biogas in landfills and its pre-treatment, and the infrastructure for the CO_2 removal process and to manage the waste generated. The transport of the reagents was excluded from the LCA study, but it was included in an uncertainty analysis discussed in section 3.3.2.

2.1.4. Literature Review

The technologies that were chosen for the study are: AwR, BABIU, HPWS, PSA, AS, Cry, MS and OPS [10].

2.2. Life Cycle Inventory

A life cycle inventory was conducted on the eight chosen technologies. Information on the AwR and BABIU process was obtained through direct email communication and information request forms sent to the Universities developing these technologies, in the framework of the ongoing Life project. Actually, the information for the AwR and BABIU have to be considered preliminary as it is the results of the laboratory analysis phase of the project and has been upscaled to industry size.

Information for the HPWS was obtained through email communications and questionnaires received from representatives of two manufacturers, Greenlane Biogas (part of the Flotech Group) and DMT Environmental Technologies. Information for the other technologies was obtained through literature review. The median point was chosen for information that had more than one value.

Information for reagents used in certain processes was not obtainable and therefore was not included in the study, as in these cases their impact could be considered negligible [10].

Data for the LCA was complemented by the Ecoinvent 2.2 [11] and GaBi PE databases [12] and inventory data for Spain was used. The inventory data used can be found in Table 1.

Table 1. Life cycle inventory data for biogas upgrading technologies per 1 kWh of biomethane (functional unit)

		BABIU	AwR	HPWS	PSA	OPS	AS	MS	Cry	reference
Inputs	Electricity (kWh) [11]	0.017	0.009	0.042	0.051	0.060	0.024	0.068	0.070	[2,3,13-22]
	KOH (kg) [11]		0.087							[19]
	H_2O (kg) [11]		1.468	0.025						[19,21,22]
	N_2 (kg) [12]	0.015								[20]
	DEA (kg) [11]						0.0002			[23]
	BA (kg)	8.890								[20]
	APC (kg)		1.018							[19]
	Diesel (kg) [11]	0.002								[20]
	Biogas (m3)	0.203	0.206	0.203	0.209	0.210	0.202	0.233	0.203	
	Heat (kWh) [11]					0.031	0.109			[14,17,24]
Properties	Biomethane purity (%)	90.3	96.7	98	97.5	97	99	85	98	[2,3,14,16-22,25]
	Methane loss (%)	0.78	2.3	1	3.5	4	0.1	13.5	0.65	[2,3,13-16,18-22,25]

2.3. Life Cycle Impact Assessment

The LCA was run using the program GaBi 4.4. The impact indicator selected for this study is the Global Warming Potential, 100 years [g CO_2 equiv.] from the CML 2001 method [26]. For this impact indicator positive values mean that CO_2 is being emitted and therefore is considered as a negative impact on the environment. Meanwhile negative values mean that CO_2 is removed from the environment and therefore is seen as a positive impact to the environment, or as a CO_2 savings.

The following assumptions were taken into consideration. The methane that is upgraded (also referred to as biomethane) and used as a substitute for natural gas down the line is considered as a CO_2 savings. The CO_2 originally contained in the biogas can either be considered CO_2 neutral if it is released back into the environment or as a savings if it is stored. The methane slip (methane loss) of each process is considered as a CO_2 emission.

As the methane slip and the final biomethane concentration is a property that is inherent to each technology, a sensitivity analysis was performed to ensure that the end results were independent of these factors. A sensitivity analysis was also preformed to evaluate possible changes once the novel technologies reach industrial scale. As well, two uncertainty analyses were also performed to explore the effects on CO_2 emissions in: the regeneration rate in AwR, the distance between a municipal solid waste incinerator and AwR and BABIU facilities, and the effect of the country where the upgrading plant is located.

2.4 Material Flow Analysis

BABIU and AwR are currently being developed with the goal of applying it to waste treatment processes (Anaerobic Digesters (AD) and landfills) while using waste from another waste treatment process (MSWI). Therefore it is important to study the flows of waste to see whether there would be enough Bottom ash (BA) and air pollution control (APC) residues from MSWI for BABIU and AwR, respectively.

Therefore a MFA was conducted on the municipal waste flows of Spain in 2008. This data was obtained through literature reviews and personal communications with people in the field [27-31]. Once the waste flow was determined three scenarios were planted and explored.

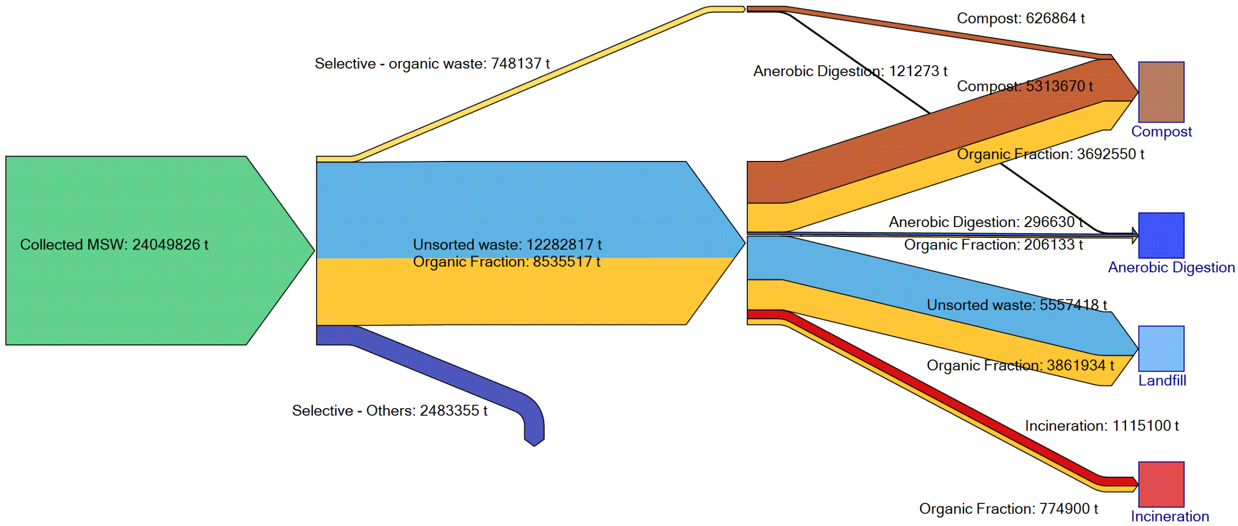

Fig. 2. Urban waste flow of Spain for2008

The amount of organic matter (OM) within the flow of unsorted waste was calculated at 41% [27]. For the potential amount of biogas generated the following assumptions were made: AD generates 115m^3 of biogas per t of OM [32], with a capture rate of 100%; and landfills generate 170 m^3 of CH_4 per t of OM [33], with a capture rate of 30%. The potential amount of BA produced was calculated as 20% of the total waste in MSWI. The potential electricity that can be generated in MSWI was estimated to be around 0.52 MWh/t of waste and was determined based on information provided for a MSWI in Barcelona in 2008 [34].

3. Results and Discussion

3.1. Life Cycle Assessment

Table 2 shows the g of CO_2 saving by each of the technologies under study. The amount of CO_2 saved varies from 1400 g to almost 2000 g. The BABIU process has the lowest global warming potential (GWP) and actually the largest potential CO_2 savings, 1980 g of CO_2 eq. In general all the other processes generate about 10% more CO_2 emissions than BABIU, except for OPS and MS which generate 15% and 25% more emissions, respectively.

Table 2. Global warming potential of biogas upgrading technologies

Upgrading process	Global Warming Potential (g of CO_2 Eqv.)
BABIU	-1977
AwR	-1794
HPWS	-1766
AS	-1761
Cry	-1758
PSA	-1714
OPS	-1691
MS	-1489

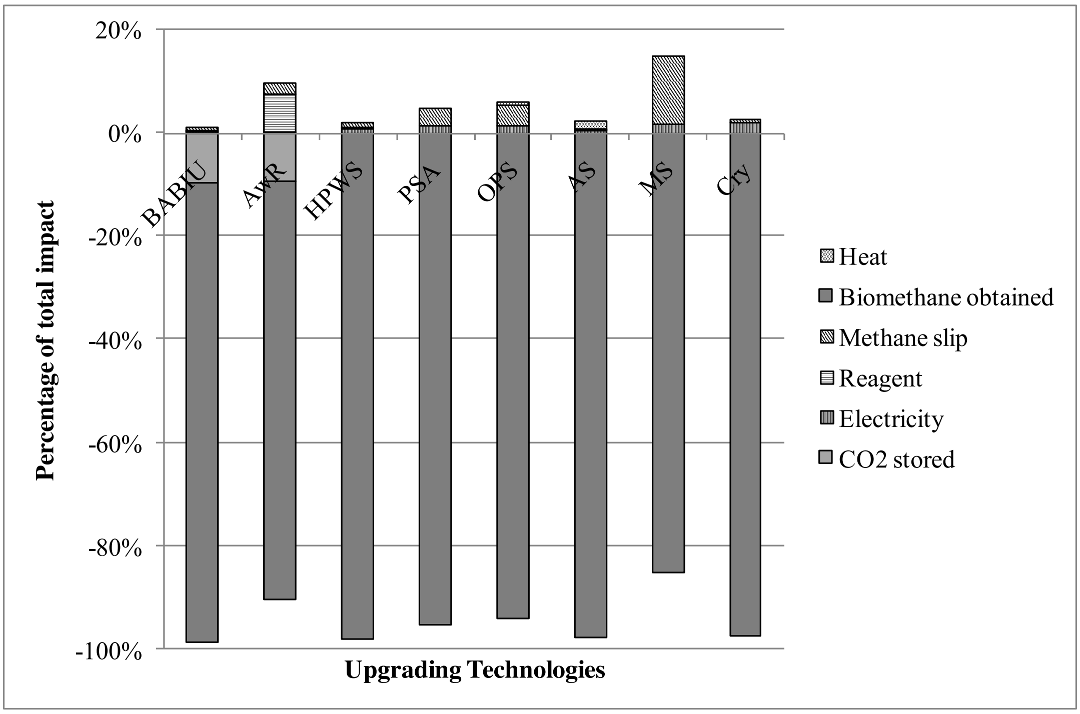

Fig. 3. Breakdown of the global warming impact of biogas upgrading technologies

Fig. 3 demonstrates the role that each component plays in the carbon balance of each technology. The biomethane processed and the CO_2 stored account for the CO_2 savings while the production of reagents, electricity and any methane slip contribute to CO_2 emissions.

The amount of CH_4 processed and turned into biomethane saves the largest amount and accounts for the fact that these technologies overall save CO_2 rather than contribute to climate change, as was demonstrated in Table 2. All the processes do emit CO_2 but the amount saved compensates for this impact. Both the BABIU and the AwR process store CO_2 and therefore this contributes to an extra savings of 198 g and 204 g of CO_2 respectively. The BABIU process had the greatest savings as it not only processes a large amount of biogas but it also produces a relatively small amount of CO_2. While AwR stores more CO_2 than BABIU it doesn't have as high of an overall CO_2 savings due to the production of KOH which counts for 8% of AwR's GWP.

For only two of the upgrading technologies, HPWS and Cry, the electricity used produced the largest amount of CO_2 emissions. For AS the production of required heat was the largest source of emissions. Meanwhile, for all the other technologies BABIU, PSA, OPS and MS, the methane slip that occurs during the upgrading process had the highest negative impact. In the case of MS, the methane slip contributes to 13% of the overall impact. For these technologies if the methane loss is reduced then their GWP would improve.

3.2. Sensitivity Analysis

Each technology has a final biomethane concentration and methane slip that is inherent to each process. It is therefore of interest to determine whether these characteristics affect their CO_2 balance. A sensitivity analysis done for all the 8 technologies showed that there is no correlation between the GWP of the technologies and the percentage of methane loss nor the final biomethane concentration.

The data obtained for the two novel technologies, BABIU and AwR consist of laboratory scale data that was scaled up to industrial scale. Therefore one can rightfully assume that once these technologies are developed to the industrial level that the data may not be the same. Though in Table 1 it is possible to see that values such as biogas input, electricity use, biomethane purity and methane loss for BABIU and AwR fall within the range established by the other six technologies that are currently on the market. From Fig. 3 one can see that the electricity use and methane loss in play a small role in the overall CO_2 impact of the technologies. Therefore one can assume that while there may be changes once the technologies are commercialized, the effect on the GWP would not be significant. This assumption is supported by a sensitivity analysis conducted where the amount of electricity used by both AwR and BABIU was increased to 0.07 kWh (which is the higher end of the electricity use by commercialized technologies). Applying this new value only reduced the CO_2 savings by less than 1.5 %.

3.3. Uncertainty Analysis

3.3.1. Reagent use in AwR

As was seen in Fig. 3, one of the largest sources of CO_2 for the AwR is the production of the alkaline reagent KOH. Currently, the regeneration rate is around 70%, therefore it was decided to study if improving the regeneration rate would improve the technology enough so that it could be comparable to BABIU and others on the market. As well NaOH is another base that is of interest for this process therefore it was also used in this comparison. The AwR using each base at different regeneration rates were compared to BABIU, AS and HPWS.

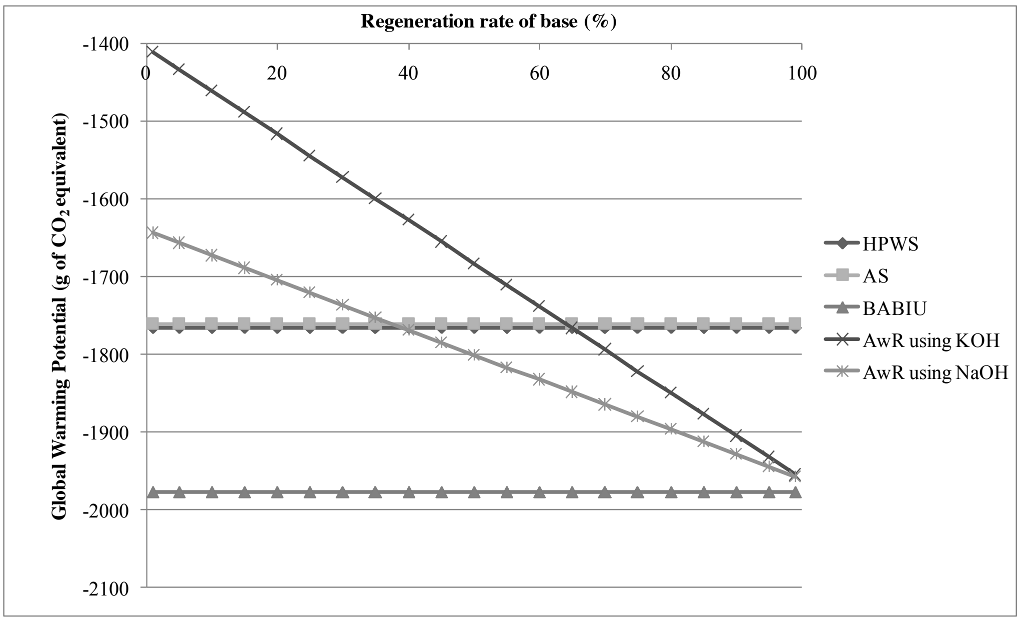

Fig. 4. Comparison of the global warming potential of using KOH and NaOH at varying regeneration rates in AwR

As can be seen in Fig. 4 even if for AwR the regeneration rate of both KOH and NaOH is improved to 99%, BABIU is still the technology with the greatest CO_2 savings. This is due to the fact that the AwR process has a slightly higher methane slip than BABIU. Though, since both of these technologies are in the development stage the methane slip may improve for both before commercialization.

Using NaOH instead of KOH will result in a greater CO_2 savings for AwR. While using KOH, AwR passed HPWS at a 65% regeneration rate but NaOH passed HPWS at a 40% regeneration rate. If the regeneration rates of either bases is improved a greater CO_2 savings is achieved, though if the regeneration rate is not improved and NaOH is substituted for KOH then an additional savings of 71 g can be achieved.

3.3.2. Transport distance and location of technology

A variable in the implementation of the novel technologies that could affect the final CO_2 emissions generated is the location of where the technology is installed. This pertains to both the distance between the upgrading plant and a municipal solid waste incinerator (MSWI), and the country where the upgrading plant is located.

As the novel technologies depend on waste coming from MSWI it is important to determine how the distance between the MSWI and the location of the upgrading technology affects the GWP. As well, large amounts of the waste are needed to run the system, for BABIU it requires 9 kg of bottom ash (BA) and 1 kg of air pollution control residues (APC) for AwR, per functional unit of 1 kWh of biomethane. It was decided to explore the impact related to transport by truck on a small scale with a distance up to 300km.

The electricity production mix of the country where the technology is installed could have an effect on the GWP. For the LCA study the inventory data used was for Spain. We decided to use also the electricity production mix for Italy as the pilot plant of BABIU and AwR are presently located there.

BABIU and AwR were compared to HPWS and AS which are the marketed technologies that showed the greatest CO_2 savings. Though to ensure proper comparability, the energy mixes of both Spain and Italy were used for all four technologies. As well a travel of 50km by truck was applied to any additional reagents used for AwR, BABIU and the amine used in AS.

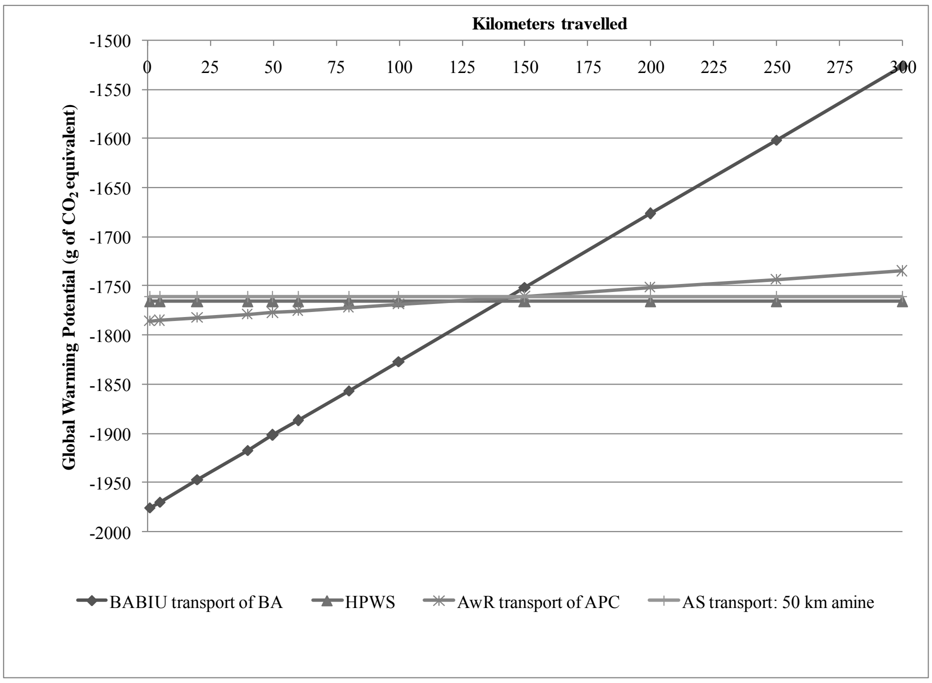

Fig. 5. Comparison of global warming potential of distance of transport of bottom ash for BABIU and APC of AwR.

As can be seen in Fig. 5 the impact of the distance travelled becomes increasingly significant when the amount of waste (APC for AwR and BA for BABIU) transported is increased. From 0 to 125 km the BABIU process still shows the greatest CO_2 savings. At around 145 km the AwR process and the BABIU process have the same CO_2 savings. At distances greater than 145 km the AwR achieves a greater CO_2 savings than BABIU, but at the same time they both have a lower CO_2 savings than HPWS and AS. When the distance between the MSWI and a BABIU plant reaches around 1315 km the impact from transport becomes higher than any CO_2 savings and the process begins to have a negative impact on the environment. For AwR, this point is reach at a much further distance of around 10475 km.

As the other part of the study, it was determined that comparatively the country where the system is implemented does not have a large effect on the GWP. Overall Spain has a greater CO_2 savings than Italy but one could state that the effect is negligible. This difference exists due to the fact that Spain uses more nuclear and solar energy than Italy [11]. Only in HPWS is it possible to note a difference and that is because out of all the 4 technologies the HPWS uses the most energy, therefore highlighting better the difference between the two.

3.4 Material Flow Analysis

Both BABIU and AwR use waste coming from MSWI in order to remove CO_2 from biogas which comes from landfills or anaerobic digesters (AD). Therefore it is of interest to determine how much BA and APC would be needed and whether enough could be generated. To obtain a general idea, the waste flow of Spain in all of 2008 was studied and the hypothetical situation was applied where all of the biogas generated was upgraded through either BABIU or AwR. This was considered as scenario 1.

Fig. 2, which demonstrates the waste flow in Spain, highlights the fact that most of the unsorted waste goes to either the landfill or for composting. On the other hand, Spain currently does not treat a lot of its waste through AD or MSWI.

Table 2. Scenarios for implementation of BABIU and AwR based on municipal waste flow of Spain in 2008

	Waste received (t)	Estimated biogas production (m3)	Estimated electricity production potential (MWh)			BA from MSWI needed for BABIU (t)	APC from MSWI needed for AwR (t)	Possible BA production (t)
			MSWI	BABIU	AwR			
Scenario 1								
Anaerobic digester	624,036	37,651,670		185,476	182,570	1,648,882	185,857	
Landfill	9,419,352	393,917,300		1,940,447	1,910,077	17,250,844	1,944,459	
MSWI	1,890,000		984,007					378,000
Scenario 2								
Anaerobic digester	9,283,654	1,067,620,203		5,259,207	5,176,815	46,754,354	5,269,998	
MSWI	6,672,517		3,473,970					1,334,503
Scenario 3								
Anaerobic digester	624,036	37,651,670		185,476	182,570	1,648,882	185,857	
MSWI	11,309,352		5,888,085					2,261,870

From Table 2 it can be seen that under scenario 1 not enough waste is treated through MSWI to supply sufficient BA or APC to treat all of the biogas emitted from AD and landfills. It might be possible to have enough APC to treat biogas from AD using AwR, but there would not be enough to treat the biogas from landfills and in both cases there would not be enough BA to treat the biogas using the BABIU process.

In an ideal situation countries would have citizen that are engaged enough to ensure that all organic material (OM) is selectively collected. In scenario 2 all of this OM is treated in the AD and all unsorted non OM waste would be sent to the MSWI. While in this scenario the production of biogas is around 2.5x higher, this would in turn require almost 47,000,000 t of BA for the BABIU process and 5,000,000 t of APC for the AwR, which could not be satisfied as only 6,000,000 t of waste would be treated through MSWI.

Scenario 3 therefore focuses on increasing the amount of BA and APC generated by sending the unsorted waste that would have gone to the landfill to the MSWI instead. In this case there would only be biogas coming from AD. Applying this scenario could generate enough APC for AwR and even enough BA for BABIU. As well, the potential electricity generated through MSWI is greater than the potential electricity from biomethane obtained through upgrading landfill biogas. While this situation seems like the best possible choice, given the current infrastructure of waste management in Spain, it would not be feasible to implement. Currently there are not enough MSWI plants to handle the additional waste.

4. Conclusion

Out of the technologies that are currently on the market the HPWS and AS showed the greatest potential CO_2 savings followed by Cry. In the former and later processes the impact of electricity used plays the largest role in the CO_2 emissions generated, while for AS the production of heat played this role. In the lower end of the spectrum are located PSA, OPS and at last place MS. For all of these three technologies the impact due to the methane slip plays the largest role. If the technologies are improved in these areas then its potential CO_2 savings could possibly be improved.

The BABIU process showed the overall greatest potential CO_2 savings. Though if one starts to factor in the distance between the MSWI and the location where the technology is installed, then it rapidly decreases in CO_2 savings due to the high amount of BA that must be transported. Therefore in order for the BABIU technology to keep its position as best technology, it must be installed within 125 km of a MSWI. As well since BABIU requires a large amount of BA it was found that applying it as a biogas upgrading solution for all of Spain is not realistic. Therefore based on these two studies the installation of BABIU should be applied at a local scale where an AD plant or landfill can be found close to a MSWI. Therefore it is dependent on whether or not there is a MSWI close enough that produces sufficient BA. Meanwhile AwR, which uses less APC per functional unit, has more of a leeway in both the distance from a MSWI and the production capacity of the MSWI.

The production of the KOH used in AwR plays a large role in its CO_2 impact. If the KOH is changed to NaOH then its impact is reduced. AwR can currently obtain a base regeneration rate of 70%, if this is improved then the GWP is improved as well, though it cannot yet achieve the same CO_2 savings as for BABIU.

These novel technologies show a great potential savings mainly due to the fact that they also store the CO_2 from the biogas. If the CO_2 removed from the current technologies is stored then they may also show similar savings, though it would be necessary to factor in the impact of the storage technology as well.

Acknowledgments

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