Upcycling wastes with biogas production: An exergy and economic analysis

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SUMMARY: The massive consumption of finite resources creates high economical and environmental costs due to material dispersion and waste generation. In order to overcome this, by-products and wastes may be used, to avoid the use of virgin materials and benefit from the useful inherent energy of the material. By adding value to the material, economic and environmental performance can be improve, which is called upcycling. In this paper, an exergy and economic analysis of a biogas process is examined. In order to investigate if biogas production from wastes can upcycle materials, biogas production from a by-product from the brewing process is examined. From the analysis, the process is found to upcycle the by-product with an increase in exergy and economic benefit due to the generation of biomethane and biofertilizer. This analysis thus shows that by using by-products as such, the sustainability of the system may improve.

1. INTRODUCTION

Given the concerns for sustainable development, the availability of energy from fossil sources and their environmental effects continues to produce problems for nations worldwide. With the current availability of alternative energy sources, our dependence on fossil sources can thus be questioned. Among these, bioenergy and biofuels have great potential for development and improvement. However, many experts have criticized the environmental performance and energy efficiency of biofuel production (Wibe, 2010; Akinci, 2008; Searchinger, 2008). It is important therefore to use energy and materials efficiently. It is also demanded from the European Union under the current directives promoting the production and use of biofuels in the European Union in order to ensure sustainable biofuel production; additionally the directive promotes the production of biofuels from industrial waste and by-products (European Commision, 2009).

The production of many biofuels for transportation, especially biogas, can be achieved with by-products and wastes from other industries. By using the wastes, the biofuels may improve their energy efficiency and environmental performance in place of conventional raw materials (Martin and Eklund, 2011). Through the production of biogas and other biofuels, industrial by-products and wastes may be given added value through biofuel production in what may be called "upcycling." The aim of upcycling is to convert waste materials into new materials with higher quality or higher environmental value in order to reduce the consumption of raw materials which results in decreasing of energy usage and environmental impacts. Anaerobic digestion can represent an upcycling process, as many wastes and by-products which are either classified as hazardous or difficult to handle are subsequently processed to produce biomethane and digestate.

Thereafter, the biomethane may be used as a vehicle fuel or electricity production in addition to the digestate being used as a valuable biofertilizer (Martin and Eklund, 2011).

The aim of this paper is to identify if upcycling of industrial wastes and by-products is possible with biogas production through the use of an exergy analysis and economic analysis. In order to quantify the added-value through biogas production an analysis of a fictitious biogas plant is considered using a major by-product of brewing process, i.e. Brewer's Spent Grain (BSG). An analysis of the exergy inputs and outputs of the system will be performed for the system to review how the exergy of the wastes of an industrial process change when they are used as raw material for biogas production. Thereafter in order to identify if value may be added to industrial wastes and by-products, an economic analysis of the anaerobic digestion process is produced The system considered is limited to the biogas production plant in order to analyze the added value of the production process from the input of brewer's spent grain to the output of products, including biomethane and biofertilizer. Employment of the products and transportation has not been considered in the analysis as the aim of the analysis is to investigate the added value from the biogas production process of a given substrate. Data for the analysis has been obtained from scientific articles, reports and industry homepages and is assumed to take place in Swedish conditions (Parsapour, 2012).

2. BACKGROUND

2.1 The biogas process

Biogas, is a gaseous fuel produced by the anaerobic digestion of organic material. The term biogas is typically used to denote upgraded version of the raw gas produced in the anaerobic reaction. This raw gas, depending upon many properties of the digester and raw material used, typically contains around 60 percent methane, 30 percent carbon dioxide and 10 percent additional gases, including hydrogen sulfide, hydrogen, nitrogen, ammonia and carbon monoxide. Upgrading thereafter performed using an array of techniques, including water scrubbing, to extract the biogas, which contains around 98% methane (Linköpings kommun, 2008; Svensk Biogas AB, 2009). This biogas output is refered to in the text hereafter as biomethane, while the process refers to biogas.

The organic material used for biogas production can include inputs such as agricultural, industrial and household wastes (Linköpings kommun, 2008; Svensk Biogas AB, 2009). Several by-products are simultaneously created during the biogas process, including solid digestate and liquid digestate. These have applications as bio-fertilizers or substrates for bioenergy product, i.e. use in CHP plants (Kratzeisen et al., 2010). Other gases produced during the process, e.g. carbon dioxide, hydrogen, hydrogen sulfide and other gases, may have further applications though they are usually released to the atmosphere (Lantz et al., 2007; Svensk Biogas AB, 2009).

2.2 Industrial Ecology, Exergy and Upcycling

Worldwide, nations are confronted with the massive consumption of finite resources which are extracted and refined at high economical and environmental costs and create wastes which may be harmful to human and ecological health. The research area of industrial ecology was developed to combat this problem with the aim of minimizing wastes through circular material and energy flows where natural ecosystems provide examples to be mimicked by industry (Lowe, 2001). Industrial ecology can therefore be described as a broad holistic framework consisting of tools, principles and perspectives borrowed and adapted from ecology for the analysis of industrial systems (Lowe & Evans, 1995; Lowenthal & Kastenberg, 1998).

Minimizing wastes and circular flows of material and energy however, are hampered by insufficient definitions of consumption and recycling. What can be quantified are the "throughput" and "degredation" as a measure of the flowrate of materials passing through a consumptive process (Connelly and Koshland, 1997). However, most studies only address the throughput of materials and energy (Connelly and Koshland, 1997; Karlsson and Wolf, 2008; Wolf and Karlsson, 2008).

In order to have a complete review of consumption, the degredation of materials and energy through industrial systems must also be addressed. Despite this, degredation has no coherent definition. For example, the loss of economic value is insufficient, because physical properties of the materials, as well as the scarcity are not addressed. Therefore, in order to measure quality and degredation, the employment of the second law of thermodynamics can be used. As such, degradation can indicate the general increase of entropy, or the amount of exergy (usefulness or quality) loss (Connelly and Koshland, 1997). In this respect, degradation represents the second law of thermodynamics, while throughput represents the first law.

In the industrial ecology literature, reuse of materials can be divided into three categories, 1) cascading, 2) recirculation and 3) upgrading. Cascading refers to the conversion of consumed material to a lower quality. Recirculation is the reuse of non-consumed material in a process. Upgrading refers to returning the consumed material to a higher quality than its pre-consumed state or otherwise converting it into its pre-consumed condition (Connelly and Koshland, 1997). According to Martin and Eklund (2011) biogas production processes may be seen as a means to add value to wastes and by-products through upcycling. In this paper, the upgrading category is key in the analysis of whether the biogas plant may act as an "upcycler" to upgrade the quality of brewing by-product into other valuable products. The three material cycling definitions aforementioned could be explained also through their change in exergy. In cascading, materials cascade from low exergy (high entropy) waste streams to a lower exergy (higher entropy) feedstock and does not return the waste to the quality of its pre-consumed state, i.e. a loss of exergy. Recirculation of materials uses the same material several times in a process, without significant degredation, therefore exergy is not lost in recirculation. In upgrading, the exergy and quality of the material is increased from the pre-consumed state through the upgrading of the product or creation of new products.

2.3 Exergy, Entropy and Sustainability

Sustainability is a broad concept, with many definitions for differing disciplines (Lems et al., 2004). What is common to most definitions, in regards to consumption and waste, is that consumption of materials and generation of wastes should be constrained to acceptable level. This "acceptable level", indicates that resources should not be consumed faster than the rate of renewal, and generation of wastes should not exceed the carrying capacity of the surrounding ecosystem (Bakshi and Fiksel, 2003). However, measuring this acceptable level has been difficult due to a lack of tools, techniques and understanding of the environmental, economic and social issues related to the surrounding environment. Despite this, several authors have made a link between the second law of thermodynamics and sustainability by considering entropy as a measure for sustainability (Hornbogen, 2003; Wall, 2010).

Using exergy and entropy to measure sustainability, gives important insight into how effective material and energy are used in a system. Systems are not sustainable if they consume exergy resources at a larger rate than that at which they are renewed (Wall, 2010), i.e. decreasing exergy. Therefore the increase of entropy, is a meaure of the systems inherent chaos or disorder, thus moving the system away from sustainability, see Figure X below.

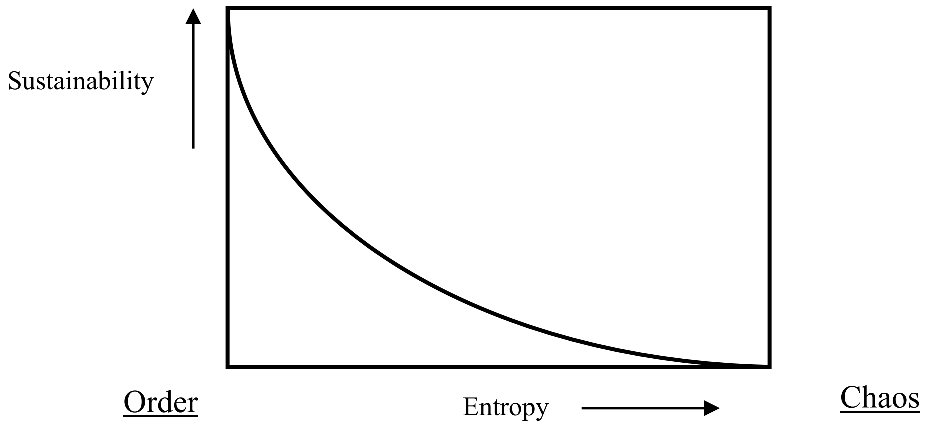

Figure 1. Relative of sustainability decreases with increasing of entropy (Hornbogen, 2003)

Minimizing the increase of entropy, i.e. minimizing the exergy loss, provides a more sustainable system. However, the increase of entropy is inevitable in our industrial processes, though the efficiency can be bettered. As such, entropy and exergy analysis could be a valuable tool from both economic and environmental viewpoints. However, the dispersion of matter must also be considered, as the biosphere and technosphere have general tendency toward increasing entropy. In all physical transformations matter is not only restructured, energy is also dissipated as heat (Hornbogen, 2003).

2.4 Eco-Thermodynamics

The economy can be viewed as an open subsystem of a larger closed environmental system, i.e. the Earth, which extracts useable energy and material and returns wastes to the surrounding environment (McMahon and Mrozek, 1997). See Figure 2 below for a representation of the exchanges between the economy and its surroundings. When reviewing this system it is apparent that energy is receieved from outside the closed system, i.e. from the solar system. However, materials and energy are finite and the input of material from the solar system is (McMahon and Mrozek, 1997).

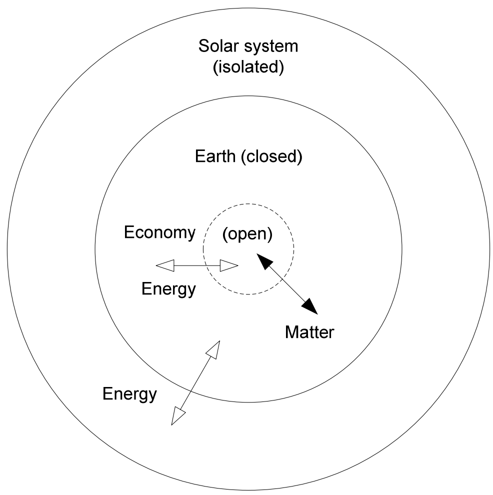

Figure 2. Hierarchy of physical and economic systems

Upon reviewing the exchanges from Figure 2, it is apparent that the first and second laws of thermodynamics apply not only to energy and material assessments, but they are useful in economic theory. Ayres (1998) refers to the application of these laws of thermodymics in economic therory as eco-thermodynamics. Using the first law of thermodynamics, implies that raw material inputs to economic processes are not consumed, and that the desired raw materials extracted from the environment eventually return to environment again as unwanted wastes. The second law of thermodymaics implies that in a closed system, upon physical transformations, the entropy of the system increases. This entropy increase continues to rise until it reaches a maximum state. Furthermore, when various systems interact, the total sum of their entropy tends to increase over time (Ayres, 1998; Baumgärtner et al., 2003).

An example is provided in Figure 3, which ecological economomists use to view the world. In this example, the world is seen as a closed system. By moving downward in the hourglass the entropy increases, i.e.the consumption of resources such as fossil fuels and minerals with low entropy causes the generation of useless wastes with high entropy (Eriksson and Andersson, 2010). Solar radiation is considered renewable, and flows to the bottom of the hourglass. However, terestrial stocks (from previous solar radiation accumulation in the form of coal and oil), are not renewable and will deplete. According to the hourglass example, consumption should be limited and the use of renewable resources will become necessary(Eriksson and Andersson, 2010).

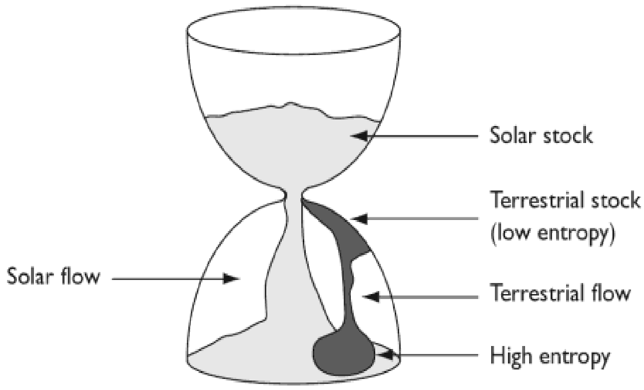

Figure 3. The entropy hourglass (Eriksson and Andersson, 2010)

Ayres (1998) discusses how the closed and cyclic model of the standard economy is incompatible with the first law of thermodynamics. In the models of standard economies, low entropy materials and energy enter the economic process with high quality, but leave the system and return to nature as high entropy wastes. This closed cycle of flows can only be sustained as long as its external exergy supply persists and by contrast, an open system is inherently unstable and unsustainable (Ayres and Ayres, 1998). Connelly has indicated that this flow can be seen in two phases which include, 1) high entropy resources such as minerals and metal ores are converted to low entropy, primary materials, then 2) these primary materials are used in industrial processes and finally returned to the environment as high entropy wastes. In order to close this material cycle, the linear flow model has to be substituted by such steps to refine high entropy wastes into low entropy materials. Material cycling needs “entropy cycling” (O’Rourke et al., 1996). Problems associated with resource depletion and pollution could draw upon thermodynamic laws in order to promote further understanding between the economy and environment (Jowsey, 2007).

3. METHODOLOGY

3.1 The Case

A fictional biogas system has been set up, named BIOLIU. It is assumed that 60,000 tonnes of BSG, 20% dry matter content, is used as the main input to the digester. It is assumed that one tonne of BSG will produce 98 Nm^3 of methane. Furthermore, 85% of input BSG will remain as digestate for which 90% can be used for biofertilizer (Garcia, 2005; Berglund, 2006; Sežun et al., 2010). The electricity consumption is assumed to amount to 18 kWh per tonne of BSG plus 0.75 kWh for upgrading per cubic biomethane produced (Murphy and McCarthy, 2005; Berglund and Börjesson, 2006). The required heat for anaerobic digestion process is 46 kWh per tonne of of BSG (Murphy and McCarthy, 2005). Heat is assumed to be provided by an external heating source such as industrial steam or from district heating system (around 60° C). It has been assumed that the heat consumption of biogas power plant in this study is in the form of steam with the amount of 655 kg per 1 tonne of methane produced. Water consumption, has been assumed to be input at a 4:1 ratio, i.e. for every tonne of dried BSG, 4 tonnes of water are used (Onwosi and Okereke, 2009). Water consumption for the upgrading process is assumed to amount to 1 liter per m^3 of raw gas produced (Benjaminsson et al., 2010). Total CO_2 released from the process is assumed to be equivalent to 35% of the total raw gas output. Inputs and outputs of the system are summarized in Table 1. More information about the assumptions, calculations and data can be obtained from a previous study by Parsapour (2012).

Table 1. Input-Output of BIOLIU biogas plant

Input	*Amount*	*Unit*
Brewer's Spent Grain (BSG) (wet)	60,000	Tonne/year
Electricity	5,490,000	kWh
Heat	2,760,000	kWh
Water	57,046	m^3/year
Output	*Amount*	*Unit*
Methane (CH4)	5,880,000	Nm^3/year
Bio-Fertilizer (Digestate)	45,900	Tonne/year
CO_2	3,166,153	m^3

3.2 Exergy Analysis

The exergy analysis of the biogas plant includes inputs and outputs to the biogas system and has been produced in several steps. The first step includes defning the system boundaries. Thereafter, the the exergy of different processes can be calculated. The second step is to calculate the exergy of substances input and output to the system. Thereafter, the exergy of utilities is calculated. Finally a compilation of the inputs and outputs is computed in order to find the exergy balance of primary inputs and outputs.

3.2.1 System Boundary

The system boundaries of the exergy analysis include the input of BSG and utilities as well as the outputs of the system including biogas, digestate and other gases as well as exergy losses in the form of heat. See Figure 4 for a representation of inputs and outputs of the system. The inputs and outputs are calculated for flows in and out of the biogas plant, therefore further use of the bio-methane and digestate are not included in the analysis. Furthermore, exergy losses from the transfer of utilities is not included in the calculations.

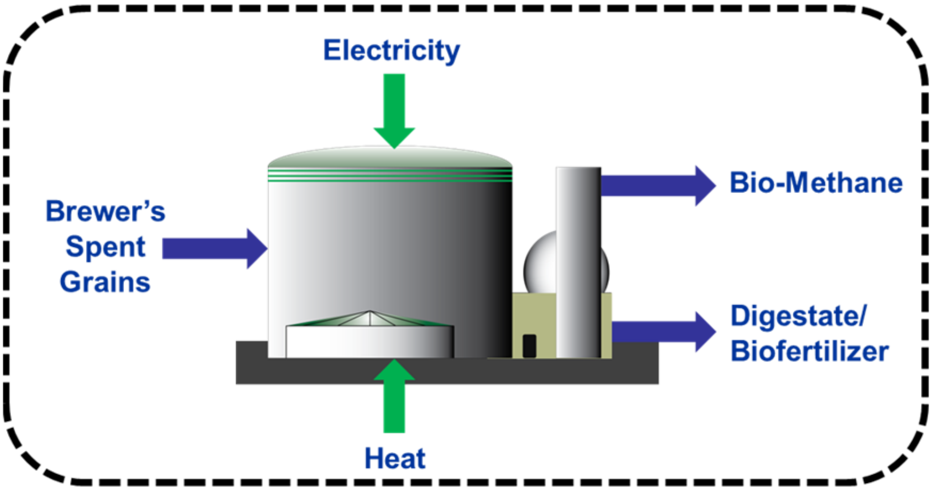

Figure 4: System boundaries of biogas production from BSG

3.2.2 Exergy of Substances

The next step of the exergy analysis is to calculate the inherent exergy of substances input and output from the biogas plant. This includes calculating the exergy of the input of BSG and water as well as outputs of digestate and other gases. The standard chemical exergy of many pure substances and compounds is available in Szargut et al. (1988) or in Appendixes B and C of (Ayres and Ayres 1999). However, if these are not available the exergy of the materials can be calculated based on the standard chemical exergy of their elements, see Equation 1 (Wall, 1977; Szargut, 2005). In this paper the symbol *E* is used for exergy, ΔG_f is formation Gibbs free energy of formation of the compound, n_e is the amount of kmol of element *e* and E_{chne} is the standard chemical exergy of the element *e* (Szargut et al., 1988).

$$E_{chn} = \Delta G_f + \sum_e n_e E_{chne} \qquad (1)$$

The Gibbs free energy of formation of many chemicals is available in standard reference sources (Ayres et al., 2001) and is a measure of the energy absorbed or released when the compound is formed from its original elements.

Table 2. Chemical elements of BSG – Before Digestion

Elements	*C*	*H*	*N*	*P*	*K*
%	54.26	7.00	3.63	0.43	0.03

For calculating the chemical exergy of the BSG, the chemical components were obtained from Huotari et al. (2008), and Onwosi and Okereke (2009), see Table 2. The chemical components of digestate were obtained from Kratzeisen (2010) and Onwosi and Okereke (2009), see Table 3. Biogas was assumed to contain 98% methane content.

Table 3. Chemical elements of BSG – After Digestion

Elements	*C*	*H*	*N*	*P*	*K*
%	37.51	4.00	3.63	0.43	0.03

3.2.3 Exergy of Utilities and Fuels

A typical normal cubic meter of methane has a calorific value of 9.6 kWh, (Swedish Gas Center, 2007), which is considered its exergy value in the current system. For utilities the exergy is calculated by multiplying the net heating value of the fuel or energy source by the exergy coefficient (Ayres et al., 2001; Talens Peiró et al., 2007). The coefficient for electricity is assumed to be 1.00 (Ayres et al., 2001).

For the exergy calculations of the process steam, both the chemical exergy (E_{ch}) and the physical exergy (E_{ph}) must be taken into account. The chemical exergy of water in gas state (528kJ/kg) can be achieved from Szargut (2005). Generally, the physical exergy can be defined by Equation 4, where h represents the specific enthalpy of steam [J/kg], h_0 is the specific enthalpy of saturated liquid water at room temperature [J/kg], s is the specific entropy of steam [J/kg K], s_0 is the specific entropy of saturated liquid water at room temperature [J/kg K] and T_0 is the room temperature [K].

$$E_{ph} = (h - h_0) - T_0(s - s_0) \qquad (4)$$

3.2.4 Exergy Balance

The exergy balance of the system should be preserved, i.e. the exergy content of the inputs must be equal to the exergy lost in a process plus the exergy content of the outputs (Ayres, 1998). In this paper, the biogas plant is treated as a "black box" and exergy inputs are compared to exergy outputs. The main material inputs will be compared with the material outputs to find whether an exergy increase is present. In this context, the exergy of the substrate BSG will be compared to the outputs of biomethane and biofertilizer. A review of all exergy inputs and outputs to the system is presented in subsequent text.

3.3 Economic Analysis

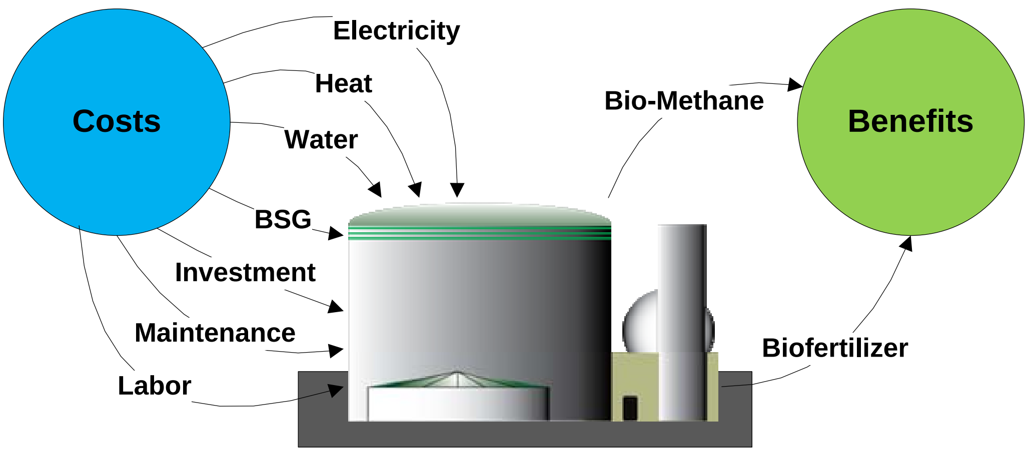

Figure 5. System boundary of the biogas plant applied in economic evaluation

A cost-benefit analysis will be used to compare the total costs of inputs and operations with the sales price of main products to understand the economic performance of the biogas plant. The economic evaluation has been made from an owner's perspective for a large scale biogas plant which is required to pay for and collect their required feedstock from different suppliers. The economic study does not include market factors and policy issues which are outside of defined biogas plant system boundary. A review of the costs and benefits from the system is provided in Figure 5.

3.4 Production Costs

Estimating the operating costs of the biogas plant is an important factor for the feasibility. The operating costs also include a number of fixed and variable costs. The costs reviewed in this paper include:

- Cost of input raw material (BSG)
- Cost of consumption of utilities such as electricity, heat and water
- Maintenance cost
- Labor cost
- Investment cost

The cost of BSG varies considerably worldwide and in the literature. However, based on these studies, the price for purchasing BSG has been assumed to be 350 SEK per tonne (wet weight) (Ben-Hamed et al., 2011; Zanker et al., 2007; Spendrups, 2011). It is assumed that the investment costs amount to 110 million SEK with the interest rate of 4% during a period of 20 years (Held et al., 2008; Berglund, 2006)and the the monthly maintenance cost have been assumed to 30,000 SEK per month. Electricity costs for the biogas plant are assumed to be 0.78 SEK/kWh and the price of district heating has been assumed to costs 600 SEK/MWh (Nordic Energy Perspectives, 2009). The cost of water is assumed to be 10 SEK/m^3 (Benjaminsson et al., 2010).

3.5 Income from Biogas Plant

It is assumed that a market is available for both the biomethane and biofertilizer produced from the biogas plant. The main product of the biogas plant is the biomethane. Biomethane sold by the biogas plant has assumed to cost 6.00 SEK/Nm^3 (Parsapour, 2012). The produced digestate from biogas production process may be used as a biofertilizer that can decrease both financial and environmental costs of using mineral fertilizers (Berglund, 2006; Lukehurst et al., 2010). The value of fertilizer depends on the available amount of nutrients in the feedstock. The important nutrients which are useful for plants are thus Nitrogen (N), Phosphorous (P) and Potassium (K) and their uptake for growth varies seasonally (Lukehurst et al., 2010). The quantities of N, P and K in the digestate have been assumed to be 3.63%, 0.43% and 0.03% respectively (Onwosi and Okereke, 2009). Thereafter, they are assumed to sell at a price of 6.70, 11.00 and 4.00 SEK respectively per kg (Biototal AB, 2012).

4. RESULTS

4.1 Exergy Analysis

The results of the exergy analysis for the BIOLIU biogas plant are summarized in Table 4.

Table 4. Exergy results of Input-Output of BIOLIU biogas plant

Input	*Exergy (MJ)*
Brewer's Spent Grain (BSG)	78,320
Electricity	4,700
Heat	1,075
Water	677
Total	*84,772*
Output	*Exergy (MJ)*
Methane (CH_4)	47,430
Bio-Fertilizer (Digestate)	37,026
Total of Main Products	*84,456*
Losses	939

The foremost exergy input to the system is the Brewer's Spent Grain. The BSG had an exergy input of 78,320 MJ. Additional inputs also include electricity, heat and water with 4,700 MJ, 1,075 MJ and 677 MJ respectively.

The major exergy outputs of the system are biomethane and biofertilizer. The exergy increase of the final products shows that the quality of BSG (78,320 MJ) is upgraded to produce biomethane (47,430 MJ) and biofertilizer (37,026 MJ), with the outputs totalling 84,456 MJ. Figure 6 illustrates the exergy inputs for the biogas plant. .

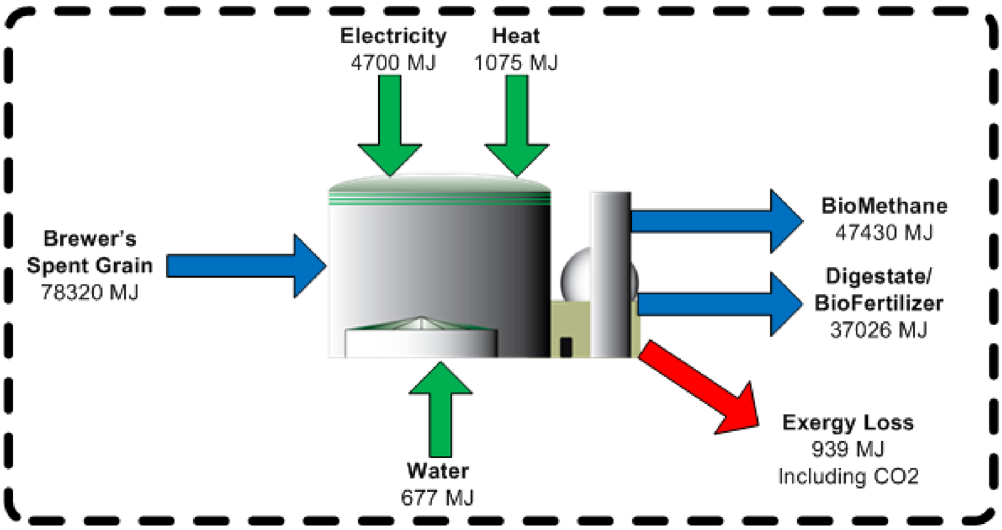

Figure 6. Exergy flow diagram of BIOLIU biogas plant

Losses to the system amount to 939 MJ, assuming carbon dioxide (CO_2) is considered as an exergy loss. The exergy efficiency of a process can be defined as the ratio between the useful exergy and the total input exergy used to carry out the process (Szargut et al., 1988). In the biogas plant of this study the exergy loss is 1.12 % of the total exergy output. Furthermore, the exergy efficiency equates to 99.60%.

4.2 Economic evaluation

The results of the economic analysis of the studied biogas plant are summarized in Table X, below. The results show that given the current assumptions, the system provides economic value to the BSG by production of biomethane and biofertilizer.

Table 5. Annual costs and benefits of BIOLIU biogas plant

Costs	*SEK (Swedish Krona)/year*
Input (BSG)	21,000,000.00
Electricity	4,282,200.00
Heat	1,656,000.00
Labor	3,600,000.00
Maintenance	360,000.00
Investment	8,093,993.00
Water	570,460.00
Total Costs	*39,562,653.00*
Income	*SEK (Swedish Krona)/year*
Biomethane (CH4)	35,280,000.00
Biofertilizer	13,381,200.00
Total Income	*48,661,200.00*
Annual Profit	9,098,547.00

The results illustrate that the production of biomethane and biofertilizer could bring an annual income of roughly 9 million SEK for the producer.

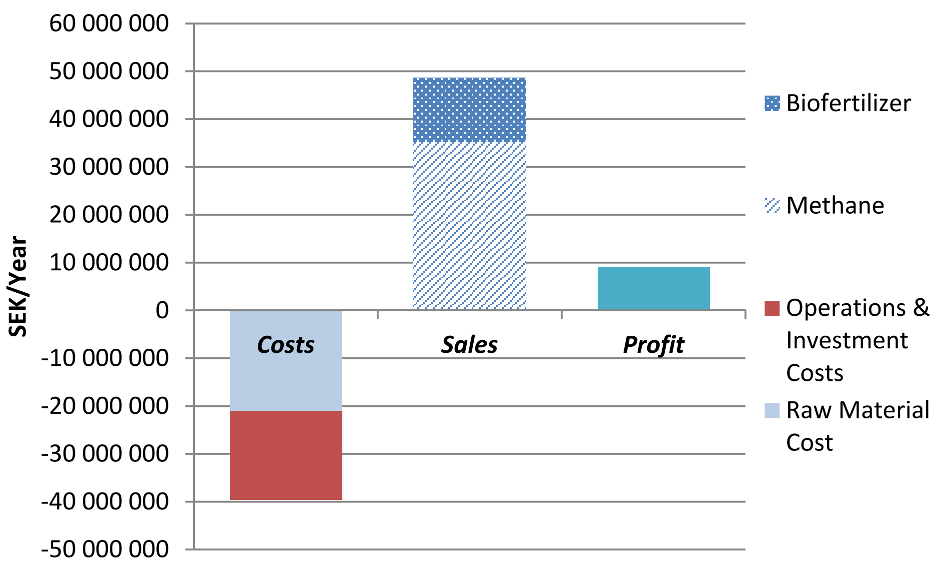

Figure 7. Cost-Benefit diagram

5. DISCUSSION

The production of an exergy and economic analysis has been employed to further understand the concept of upcycling applied to the biogas process, and to know how it can contribute to the sustainable development. In order to promote sustainable development, nature's capital must be used efficiently (Wall, 2010). In this paper, the handling of BSG to produce biomethane to substitute fossil fuels such as natural gas or petrol, has been conducted to minimize the consumption's rate of nature's capital. In a previous study, the improvments to the value and environmental performance have been described as upcycling (Martin and Eklund, 2011). However, the value in this paper has taken a different position and the exergy has also been identified as a means to quantify the change in material quality.

From the exergy analysis of the BIOLIU biogas plant the main substrate, i.e. BSG, leads to an increase in exergy for the outputs of biomethane and biofertiizer. Talens et al. (2007) report similar findings of increasing exergy in the biodiesel industry. In the study the quality of used cooking oil (30,367 MJ) may be upgraded during the production of biodiesel (31,349 MJ). Therefore, the exergy of a substance can be used as a quantity of material quality. According to Ayres et al. (2001), exergy is the most suitable indicator for the accounting of resources.

In this study, the increase of exergy demonstrates that the system moves toward order by decreasing its entropy, resulting in the decrease of material dispersion. Although every production and consumption process inevitably generates wastes and by-products (Ayres, 1998), exergy analysis can express the degree of usefulness of the system for surrounding environment and for comparison with other options. With that said, Brewer's spent grain has applications in other sectors (Mussatto, 2006) as an animal feed (Ben Hamed et al., 2011) or for combustion (Enweremadu et al., 2008). Further assessment of these applications can be examined to understand the best use of BSG from an exergy standpoint. From this study however, the use of BSG to produce biogas and biofertilizer seems a promising method to generate further exergy value.

From the economic assessment, given the chosen system, the biogas plant leads increased value for the production of biogas from BSG, even when the investment and maintenance costs are included. However, the largest costs are for the raw material, BSG. Furthermore, the income is relatively dominated by the sale of biomethane. However, many uncertainties are present for the substrate and selling prices of the products. The pricing for the biomethane and biofertilizer, are relatively sensitive since they are determined by the price of fossil fuels and fossil products. According to Parsapour (2012) in pre-study for this paper, a 50% decrease in the price of BSG results in an 80% increase in the total profit of the biogas system. However, increasing the price of BSG by 50% will impose a loss to the economy of the biogas plant. Further, due to the variation of the biofertilizer price among different seasons, the annual benefit of the biogas plant may reduce.

According to Norde (1997), in a thermodynamic world view, increasing the exergy, or decreasing the entropy, will lead to sustainable development (Norde, 1997). In contrast Bakshi and Fiksel (2003) indicate that the exergy/entropy change alone is not enough to depict sustainability. Exergy analysis and economic evaluation can be used as the sustainability indicators, but other aspects must be taken into account for the measurement of the sustainability of a system or a process (Ayres and Ayres, 1999). It is recommended that further studies on the valorisation and material quality improvements of BSG through economic and exergy analyses respective, compare the employment of BSG in other industries.

6. CONCLUSIONS

The aim of this study has been to study the exergy analysis and the economic evaluation of a biogas plant biogas from the by-product of brewing industry, Brewer's Spent Grain (BSG) to identify if the production could be classified as upcycling.

Exergy analysis of the studied biogas plant showed that the exergy of input BSG (78,320 MJ) has increased by converting into biomethane (47,430 MJ) and biofertilizer (37,026 MJ) as two useful products of the biogas production system with a combined exergy of 84,456 MJ. This increase in exergy therefore shows that an upgrade is possible.

The results of economic evaluation indicated the biogas process had economic benefits. However, the profit of the biogas plant is very sensitive to many factors, including the price of the substrate and selling price of the biogas and biofertilizer, for which the profit may vary seasonally.

Both exergy and economic analysis of the studied biogas plant showed an increase in the quality and the value of the input BSG which illustrates how the biogas plant creates value from the thermodynamic and economic point of view. Therefore, the biogas plant acts as an "upcycler." Exergy analysis and economic evaluation can be used as indicators to measure the sustainability of a system. From the analyses, the material quality can be matched with economic assessments to understand the implications of using by-products and wastes. However, the sustainability of a system depends on the other factors such as social and environmental aspects of the system.

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