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Process Evaluation of a Domestic Biogas Digester

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Abstract

Africa has launched a Life Cycle Assessment (LCA) network in conjunction with the Society of Environment Toxicology and Chemistry (SETAC), and this points to a recognized gap in LCA initiatives between developed and developing countries. Although South Africa does not have legislation on carrying-out LCA initiatives, there is a huge drive on preserving our environment, and that is evidenced through the carbon tax bill already proposed. It is due to such developments that the authors initiated an LCA initiative in the design phase of a Biogas Plant for domestic applications. Thorough LCA initiatives are notorious for being time consuming and often manipulated by organizations to “greenwash” their products. These challenges have been a stumbling block for the acceptance of LCA initiatives. The paper looked at the operation of a biogas digester process, for a biogas digester that has been developed in the University of Johannesburg. From the aforementioned process fundamental Life Cycle computation was carried out to identify the environmental impact of the product.

Keywords: Biogas Digester; Global Water Potential; Life Cylce Assessment; Water Footprint

1. Introduction

A bulk of South Africa’s energy source is still primarily driven by non-renewable fossil fuels as evidenced in Fig.1 [1]. This has led to the development of a biogas plant by the University of Johannesburg. The paper discusses the biogas digester process in particular, where the environmental impacts of the product are quantified.

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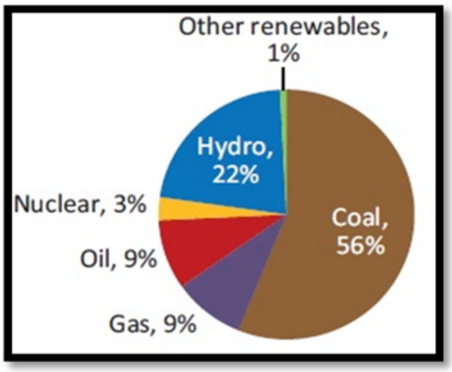

Fig. 1. South African Energy Distribution [1]

1.1. Problem Statement

There isn't a South African database that is primarily devoted into analyzing environmental impacts of products specific to the South African conditions. This has subsequently led to the use of international models for South African products and process, resulting in environmental impact assessments which are not a true reflection of what is happening locally. It is through such hindrances that the authors decided to review the fundamental calculations of Life Cycle Assessment initiatives and model environmental impacts that are reflective of South Africa.

1.2. Objectives

The paper is aimed at achieving the following objectives:

- Obtain quantifiable emissions of a biogas digestion process,
- Indicate the importance of using local data for Life Cycle Assessment initiatives,
- Raise awareness on the importance of designing for the environment;
- Comment on the feasibility of developing a local database as opposed to utilizing existing databases.

1.3. Methodology

The following methodology was followed in the development of the paper:

- Conducting a Life Cycle Assessment literature review,
- Conducting a biogas digester literature review,
- Discussion of the process investigated boundary conditions and assumptions,
- Discussion of the Life Cycle Impact Assessment calculations used, and their limitations,
- Computation of the biogas digester environmental impacts,
- Comment on the results obtained,
- Concluding remarks.

2. Literature Review

All know products and processes have an environmental impact [2]. Knowing that this is an inevitable consequence of all engineering products, designers need to be aware of these impacts and take necessary measures to minimize them right at the beginning of their product designs. In this section of the paper the authors reviewed the Life Cycle Assessment literature, and it should be noted that a number of texts in this topic (Life Cycle Assessment) discuss procedures on carrying out the initiatives, and the computational structure thereof is given less attention [3]. With that being said, the computational format of the initiative is discussed in section 4.

2.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a product or service environmental impact assessment tool used to analyze the products materials inputs and outputs from raw material to disposal and recycling thereof [4]. Thus LCA can be viewed as a cradle to grave analysis of a product or services. However, in recent years and particularly during the design phase of products, there have been other boundary conditions imposed on conventional Life Cycle Assessments and these include: cradle to gate, and gate to grave assessments [5]. The aforementioned assessments are utilized in a number of instances such as when a designer knows that two hypothetical products consume the same amount of natural resource, therefore one can ignore the environmental impact of the natural resource in a case where the two products are being compared as they would have the same environmental impact.

A Life Cycle Assessment framework is split into four phases, as proposed by the International Standards Organization (ISO). These phases indicated below seek to ensure that Life Cycle practitioners follow a certain framework in order for their results to be comparable and standardized with similar products [6] [7]:

- Goal and Scope definition: Unambiguously state the intended application, and the reasons thereof. Clearly communicate the boundary conditions, limitations, functional unit and the allocation procedure to be utilised,
- Inventory Analysis: Involves data collection and calculations procedure to be adopted for the Life Cycle Assessment,
- Impact Assessment: Deals with the evaluation of environmental impacts, and the level of importance that the impacts have on the environment,

- Life Cycle Interpretation: For one to make environmental claims or comments on the environmental impact of one process versus the other, the interpretation of a Life Cycle needs to conform to generally accepted standards, and in some case peer reviews will need to be considered depending on who the target audience for the study is (as defined in the goal and scope definition).

2.2. Biogas Digester

The primary purpose of a biogas plant is to produce methane gas which will then be used as an energy source [8]. There are different configurations of digesters, and the one being developed at the University of Johannesburg is a mesophilic anaerobic type digester. This means that the digester is configured such that ingress atmospheric air is restricted, and the fermentation of organic waste is optimized at 35ºC [9] [10]. It should be noted that the biogas digester under investigation is meant for domestic use, and the influent of the digester is freshwater coupled with domestic food waste. The temperature of the digester is maintained at a constant temperature as the bacteria fermenting the organic waste are temperature sensitive [11]. It should be noted that only the digestion process is discussed in the paper, meaning that the upstream processes i.e. purifying the methane, and the downstream processes i.e. assembly of the plant, transportation and manufacturing of the plant are excluded.

3. Boundary Conditions and Assumptions

Fig. 2 indicates the biogas digester process that was modelled. The contents of the effluent that will be released by the digester are unknown, and a more descriptive model will be developed upon knowing the contents of the effluent. The process flow in Fig. 2 was modelled using an open source LCA software known as OpenLCA.

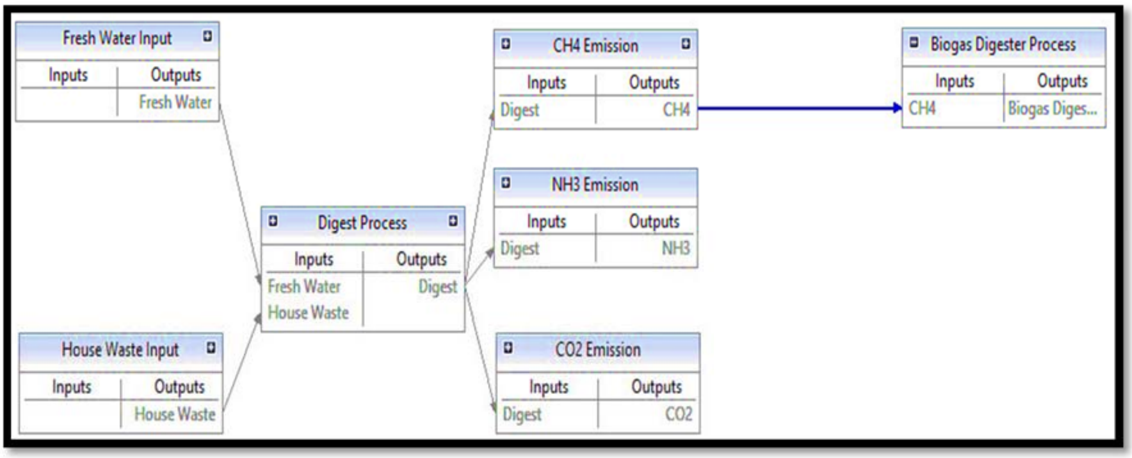

Fig. 2. Biogas Digester Process Flow

Table 1 indicates the material flow of the inputs and outputs of the biogas digestion process. The organic house waste has been modelled with generic waste content described as follows: $C_8H_{22}O_6N$. A survey was conducted to determine the minimum amount of energy required by a household in rural South Africa to light four lamps (for four hours) and cook for two hours, and it was found that a minimum of 24.6MJ/day of energy is required. Hence the functional unit of the digestion process is based on a functional unit of 24.6MJ/day. Upon the completion of the Biogas Plant model, the functional unit will be revised for the lifespan of the plant, and also take maintenance into consideration.

Table 1. Biogas Digester Inventory Analysis.

Material	Quantity	Units
Fresh Water	1.008	kg/day
Organic House Waste	0.504	kg/day
Carbon Dioxide	0.656	kg/day
Methane energy required	24.6	MJ

4. Life Cycle Impact Assessment

There are two types of calculations adopted for the model discussed in the previous section. The two calculations adapted are the Global Warming Potential (GWP), and Water Footprint (WF). The two calculations were selected primarily on the fact that biogas digesters, irrespective of their configuration make use of water, and they inevitably release greenhouse gases into the environment [12].

4.1. Global Warming Potential

Global Warming Potential (GWP), serves to quantify the environmental impact of greenhouse gases [13]. To compare different greenhouse gases a reference gas (carbon dioxide) was selected. Thus computation of Global Warming Potential is based on units of carbon dioxide equivalence [13]. Equation 1 [13] indicates the Global Warming Potential general equation.

$$i_{CO_{2eq}} = \sum_i GWP_i * m_i * CF \quad (1)$$

Where: i_{co2}=Global Warming Environmental Impact
m_i=Mass of material in the process,
CF= Correction factor;

GWP=Is the Global warming potential,

The correction factor stems from the reason that data captured has inherent uncertainty. The Pedigree matrix was developed to cater for such uncertainties. The governing equation in determining the uncertainty is as indicated in Equation 2 [14].

$$SD_{g95} = e^{\sqrt{[\ln(U_1)]^2+[\ln(U2)]^2+[\ln(U_{31})]^2+[\ln(U_{41})]^2+[\ln(U_5)]^2+[\ln(U_b)]^2}} \quad (2)$$

Where U_1=Uncertainty Factor of Precision,

U_2=Uncertainty Factor of Completeness,

U_3=Uncertainty Factor of Temporal Representativeness,

U_4=Uncertainty Factor of Geographical Representativeness,

U_5=Uncertainty Factor of Technological Representativeness;

U_b=Basic Uncertainty Factor.

The Global Warming Potential of different greenhouse gases is as given in Table 2 [15]. It should be noted that in modeling the biogas digester, methane was excluded due to the fact that there are additional processes that the methane will form part-off. Thus including methane will be assuming that it is released to the environment in this process in particular.

Table 2. Global Warming Potential for 100-year Time Horizon [15]

Common Name	GWP
Carbon Dioxide	1
Methane	25
Nitrous Oxide	298
Sulphur Hexafluoride	22800
Hydrofluorocarbons(HFC-11)	4750
Perfluorocarbons(PFC-14)	7390

4.2. Water Footprint

Water footprint is an indication of how we use this scars resource (freshwater) and for what application it is being used for [16]. Thus for the biogas digestion process, the water footprint is given in terms of kg/energy-output while Water is classified into 3 different categories, namely green, blue and grey water [17].

- Green water: Water sourced from the root zone of the soil,
- Blue water: Sourced from the surface or underground sources,
- Grey water: Quantity of freshwater necessary to mimic pollutants, so that specific water quality standards are met.

5. Impact Assessment

The Pedigree matrix parameters were selected based on the values as indicated in Table 3.

Table 3. Pedigree Matrix.

	1	2	3	4	5
Reliability	1	1.05	1.1	1.2	1.5
Completeness	1	1.02	1.05	1.1	1.2
Temporal Correlation	1	1.03	1.1	1.2	1.5
Geographical Correlation	1	1.01	1.02	1.02	1.1
Further Technological Correlation	1	1	1.2	1.5	2

From Equation 2 the standard deviation can be calculated as follows:

$$SD_{g95} = e^{\sqrt{[\ln(U_1)]^2 + [\ln(U2)]^2 + [\ln(U_{31})]^2 + [\ln(U_{41})]^2 + [\ln(U_5)]^2 + [\ln(U_b)]^2}}$$
$$= 2.29$$

The Global Warming impact is calculated as follows:

$$i_{CO_{2eq}} = \sum_i GWP_i * m_i * CF$$
$$= (0.656)(1)(+-0.0229)$$
$$\therefore i_{CO_{2eq}} = \{\min, \max\} = \{0.641, 0.671\} co_{2-eq}$$

The water footprint is computed as follows:

$$WF = \frac{Q_{water}}{Energy \quad Output}$$
$$= \frac{1.008}{24.6}$$
$$= 0.041 kg / MJ$$

6. Interpretation of Results and Conclusion

The challenge in computing environmental impacts of a product strongly rely on the availability of data. This means that although the computation of environmental impacts is relatively straight forward, the equations inputs need to be extracted some sources. Thus making the data collection in the study a time consuming process. Previous sections illustrated that the digestion process alone can potentially produce 0.671CO_2-eq greenhouse gases. The GWP of the entire model, including processes that were omitted in the computation will add on this value. It should also be noted that no expert judgement was considered in the values selected for the Pedigree matrix, and a conservative approach was taken. This means that it is probable that the greenhouse gas emissions could be lower than computed. The Water Footprint computation is straightforward, however the computation still needs to be revised once the digester prototype has been developed, and the necessary experimental data has been gathered.

From the digestion process alone, the authors believe that it is possible to develop a database specific to local conditions, however the accuracy of the database strongly hinges on the amount and availability of data. The time involved in computing the environmental impacts without the aid of utilizing a software package is yet to be quantified, as the paper only focused on a single process and a gate to grave assessment will be more involved. The authors strongly encourage the use of fundamental calculations when developing a database, as this gives the practitioner flexibility of imposing region specific values, and also highlights the limitations of specific equations.

Finally, it has been said that interpreting environmental impacts can be challenging [18], as values alone without references are difficult to comprehend. The authors are aware of this limitation, and highlight that a more convenient way to understand the environmental impact values, will have to include comparing similar products. However in the paper only one process of a plant was analyzed, and additional assumptions were made to further simplify the computation. Thus to compare the results with environmental impacts of other products will not do justice to either the product investigated, or a reference product. ISO also has strict guidelines on how comparisons should be carried out, and this again includes peer reviews and expert judgements. The values of the entire product with the upstream and downstream processes that were omitted can be used to give the product's Environmental Product Declaration (EPD) label. The EPD label does not compare similar products, but only indicates what the assessed product's environmental impact is [19]. Products with EPD labels enable the consumer to be conscious of the environmental impacts of the product that he/she is purchasing, and then they (consumers) can draw their own comparisons and conclusions about the product's environmental impacts, without the product developers comparing their product with that of the competitor.

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