Development of Life Cycle Inventory (LCI) for Sugarcane Ethanol Production in South Africa

Anup Pradhan* and Charles Mbohwa
Department of Quality and Operations Management
University of Johannesburg
Johannesburg, South Africa

***Abstract*—The Biofuels Industrial Strategy established by the government of South Africa in 2007 has emphasised the need to understand the potential benefits and consequences of developing biofuels in the country. Life cycle assessment (LCA) is a preferred tool to measure energy and environmental performances of biofuel production; however, LCA relies heavily on data and developing a life cycle inventory (LCI) plays a crucial role in any LCA studies. The lack of availability and difficulty in obtaining data from reliable sources can provide a great challenge during the process of developing biofuels LCI. This study develops a LCI database for the production of ethanol using sugarcane molasses in South Africa. The inventory includes all the input and output data associated with various sub-system of ethanol production. Relevant data are collected through national statistics and various literatures. The LCI has been developed as a first step towards the LCA studies which can assist in measuring the performance of South African ethanol development in the future.**

Keywords-life cycle inventory (LCI); sugarcane; molasses; ethanol; South Africa

I. Introduction

South African transportation sector is the second largest consumer of energy after Industrial sector, and consumes about 35% of the nation's total primary energy and emits 31% of carbon dioxide (CO_2) [1]. Due to the increasing demand of petrol in South Africa, the nation has turned from petrol exporting nation to petrol importing nation in the recent years (Figure 1). To diversify country's energy supply and reduce dependence on foreign oil, the South African government has established Biofuels Industrial Strategy in 2007. The strategy aimed to achieve biofuel blends of 2% by 2013 and recommended sugarcane and sugar beet as ethanol feedstock, but excluded using maize citing food security issues [2].

Ethanol is perceived as a renewable fuel which reduces emissions. A report by the government of South Africa estimated that ethanol can reduce greenhouse gas (GHG) emissions by 30% [3]. In addition, ethanol plants also assist in creating job opportunities [4]. According to the Biofuels Industrial Strategy, ethanol falls outside the fuel tax net and thus will enjoy 100% exempt from fuel tax [2, 4]. In 2012, the regulation was revised allowing for ethanol blends of 2% up to 10% [5]. South Africa produces about 16000 litres of ethanol per day [6] through small to medium scale plants using sugarcane molasses, which is mostly used for non-fuel purposes (e.g. solvent, liquor, etc.) [7].

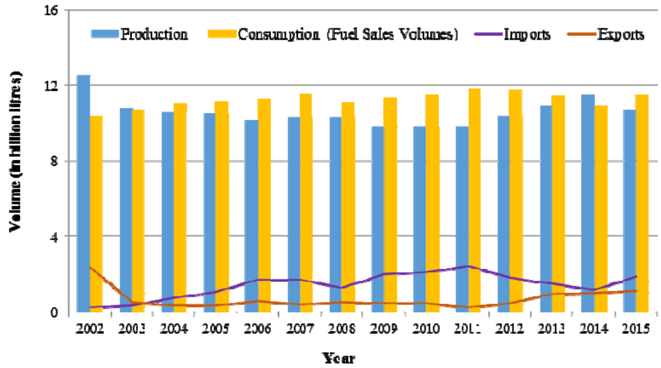

Figure 1. Production, consumption, imports and exports of petrol fuel in South Africa [8]

Despite being a renewable fuel, the production of ethanol require usage of non-renewable sources (e.g. fossil fuel, chemical fertilizers, etc.). Life Cycle Assessment (LCA) can be used to measure energy and environmental impacts of producing ethanol. LCA is conducted following ISO standards, and includes: (i) Goal and scope definition, including system boundary; (ii) Life cycle inventory (LCI) analysis; (iii) Impact assessment; and (iv) Interpretation [9].

Globally, several life cycle assessment (LCA) studies have been conducted showing higher energy yields and greenhouse gas (GHG) savings from sugarcane based ethanol [4, 10-13]. Since, few large scale commercial ethanol plants are in pipeline [14], it is sensible to measure the performance of ethanol production in South Africa over its life cycle. LCA relies heavily on data and developing life cycle inventory (LCI) plays a crucial role in any LCA studies. LCI provides the account of all the inputs and outputs of processes occurring during the life-cycle of a product. The collection of reliable data for each sub-system is one of the greatest challenges in developing ethanol LCI. This study develops a LCI of producing ethanol using molasses in South Africa, which can be helpful in future ethanol LCA studies.

II. System Boundary

A system boundary defines what to be included and what to be excluded from the production processes. In order to make

LCA meaningful, a system boundary must include all significant sources of energy. However, it becomes impossible to include all the energy used over the life cycle of a product, hence a care must be taken while excluding sub-systems from the system boundary used in LCA [9]. The system boundary for the production of ethanol includes agricultural, industrial and distribution sectors (Figure 1).

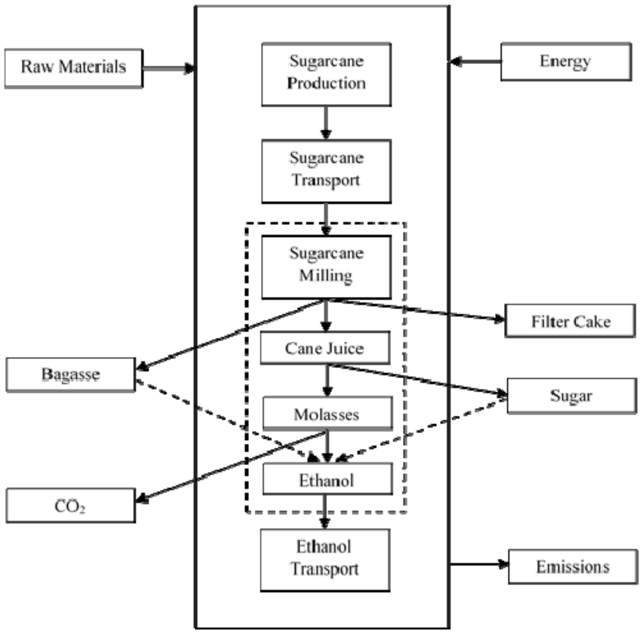

Figure 2. Ethanol production from sugarcane

Agricultural sector includes the production and transportation of sugarcane. Different farming activities are required during the production of sugarcane, most of which requires using non-renewable fuels such as diesel, petrol. Various fertilizers and pesticides are also applied to improve yield. The harvested sugarcane is transported to the processing plant using trucks or rails.

Industrial sector includes sugarcane milling and ethanol production. In the industrial sector, sugarcane is crushed to produce cane juice, along with filter cake (a residue from filtration of cane juice) and bagasse (a fiber residue). Filter cake can be used as field fertilizer and bagasse can be used as fuel to meet the energy requirements of the operating site or converted to cellulosic ethanol. In ethanol-only process, cane juice is fermented to ethanol, whereas sugar-ethanol process uses cane juice to produce sugar crystals and molasses (a residual from refining). Molasses, which contains residual sucrose and other sugars, is fermented to produce ethanol.

Distribution sector includes transportation of ethanol for distribution. The final ethanol produced in the processing plant is loaded in trucks and transported to blending or distribution facilities.

III. LIFE CYCLE INVENTORY (LCI)

Life cycle inventory (LCI) keeps the account of all the inventory entering and leaving the system boundary [9]. For this study, LCI is developed using data and information obtained from national statistics and literatures. The average sugarcane yield in last five years is estimated to be about 63.5 t/ha (Table 1).

TABLE I. AREA HARVESTED, PRODUCTION AND YIELD OF SUGARCANE IN SOUTH AFRICA [15]

Season	2010/ 2011	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015	Five Year Average
Area harvested (1000 ha)	271	252	257	266	272	264
Sugarcane production (Million ton)	16.02	16.80	17.28	20.03	17.76	17.58
Sugarcane yield (t/ha)	59.08	62.06	63.60	67.52	65.14	63.48

About 90% of the harvested area is burnt before harvesting sugarcane to remove leaves and tops. Sugarcane is then transported to sugar mills using trucks (94%) and rail (6%). The average distance of sugarcane transportation is about 90 km for trucks and 50 km for rail [16]. Standalone ethanol distillery plants purchase and haul molasses from sugar mills to distillery using diesel trucks carrying an average load of 30 tons and covering an average distance of 70 km [17].

Average sugar production is about 2.04 million tons a year at sugarcane to sugar conversion ratio of 8.64:1 (Table 2). Not all sugar produced in South Africa is consumed and surplus sugar is mostly exported to neighboring countries. Table 2 presents the surplus amount of sugarcane and associated amount of potential ethanol. For instance, about 3.62 million tonnes of sugarcane was estimated to be surplus in 2014/15, which translated to about 267.3 million litres of ethanol. An ethanol productivity of 19.5 gallon per t of sugarcane [18] was used to estimate the amount of ethanol from surplus sugarcane.

TABLE II. SUGAR PRODUCTION, CONSUMPTION AND SURPLUSES [15]

Season	2010/ 2011	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015
Sugar production (Million ton)	1.92	1.83	1.96	2.35	2.12
Sugar consumption (Million ton)	1.55	1.69	1.61	1.55	1.69
Surplus sugar (Million ton)	0.37	0.14	0.35	0.80	0.43
Tons cane to 1 ton sugar	8.35	9.17	8.81	8.51	8.38
Surplus sugarcane (Million ton)	3.09	1.31	3.09	6.83	3.62
Ethanol from surplus sugarcane (million litres)	227.5	96.7	227.8	504.4	267.3

The amount and emissions of inputs and outputs associated with the production of ethanol using molasses is presented in table 3. The numbers in the table do not include allocation for co-products. Due to multiple co-productions, the choice of allocation can play a critical role in estimating LCA results of molasses-ethanol process.

TABLE III. LCI DATABASE PER UNIT PROCESSES FOR ETHANOL PRODUCTION USING MOLASSES IN SOUTH AFRICA

Inputs/ Outputs	Amount	CO_2 Emission (g)	CH_4 Emission (g)	N_2O Emission (g)
***Sugarcane Production*:**	(per t cane)	(per t cane) [19]	(per t cane) [19]	(per t cane) [19]
Seed				
Nitrogen (N)	1.86 kg [16]	2994	3.14	1.7802
Phosphorus (P)	0.46 kg [16]	116	0.21	0.0021
Potassium (K)	1.93 kg [16]	123	0.19	0.0018
Herbicide	26.9 g [19]	546	0.80	0.0059
Insecticide	2.21 g [19]	3093	4.78	0.0403
Irrigation	263 m^3 [16]			
Electricity	3.34 kWh [16]	72	0.14	0.0070
Diesel	1.36 L [17]	1492	1.72	0.0180
Cane Burning	4.33 kg [16]	315973	514	13.328
Soil N_2O Emission	1.33% of N [19]			
CO_2 Uptake from Air		-349067		
***Sugarcane Transport*:**	(per t cane)	(per t cane)	(per t cane)	(per t cane)
Truck (Diesel)	6.76 L [16]	3774 [19]	4.33 [19]	0.0895 [19]
Rail	34 MJ [16]			
***Cane Milling*:**				
I. <u>Sugar Production</u>	(per t sugar)	(per t sugar)	(per t sugar)	(per t sugar)
Coal	73 kg [16]	894 [20]	34.63 [20]	8.658 [20]
Steam	4502 kg [16]			
Electricity	303 kWh [16]	623 [19]	1.17 [19]	0.061 [19]
Lime	5.1 kg [17]	26780 [19]	41.41 [19]	0.349 [19]
Water	5.2 m^3 [16]			
Liquid Effluent	0.1 L [17]			
II. <u>Molasses to Ethanol</u>	(per L EtOH)	(per L EtOH)	(per L EtOH)	(per L EtOH)
Coal	0.75 kg [17]	94 [20]	3.64 [20]	0.910 [20]
Steam	16.2 MJ [17]			
Electricity	251 Wh [17]	8 [19]	0.014 [19]	0.0007 [19]
Sulphuric acid	3.8 g [17]	0.17 [19]	0.00022 [19]	0.0000033 [19]
Water	16.4 L [17]			
CO_2 (Fossil)	1.89 kg [17]			
CO_2 (Renewable)	0.75 kg [17]			
Liquid Effluent	21.4 L [17]			
***Ethanol T&D*:**	(per L EtOH)	(per L EtOH)	(per L EtOH)	(per L EtOH)
Truck (Diesel)	0.37 MJ [19]	28 [19]	0.04 [19]	0.0007 [19]

The amount of filter cake, bagasse and molasses produced as co-products during sugar production accounts for 6.8%, 27.8% and 4.1% of sugarcane respectively [16]. Molasses contains about 60% of fermentable sugar and sugarcane fibre left after juice extraction contains carbohydrates, which can both be used to produce ethanol [4]. Ethanol produced from these co-products does not compete with food production.

About 4.3 kg of molasses is required to produce a litre of ethanol, with an energy equivalence of 21.5 MJ [17]. Additional 1.27 litre of ethanol can be produced from a kg of bagasse [21]. Excess bagasse can also be used to generate electricity that can be used in operating site or sold to grid. About 150 kWh of electricity can be produced using 280 kg of bagasse obtained from crushing a ton of sugarcane at about 23.5% efficiency [22]. The GHG emission due to land use change (LUC) has been reported to be about 16 g CO2e for sugarcane ethanol [10]. No additional land is required to produce molasses and bagasse.

IV. CONCLUSION

A detailed LCI database for the production of ethanol using sugarcane molasses in South Africa was developed as a first step towards the future ethanol LCA studies. While developing LCI, incomplete data are the rule rather than the exception. The quality of data can significantly influence the results; therefore, data were collected from reliable resources and cross-checked with other sources for validation. The LCI database needs to be updated frequently whenever new dataset becomes available. National data also depicts that the South African sugar industry is producing surplus amount of sugar which can be used to produce up to 0.5 billion litres of ethanol without competing with the food production.

ACKNOWLEDGMENT

The authors wish to acknowledge National Research Foundation (NRF) of South Africa and the University of Johannesburg for providing funds for this study.

REFERENCES

[1] DoE, "Energy balances," Department of Energy, Energy Statistics, South Africa, 2017. Retrieved from http://www.energy.gov.za/ on April 1, 2017.

[2] DoME, "Biofuels Industrial Strategy of the Republic of South Africa," Department of Minerals and Energy, South Africa, 2007.

[3] DoE, "Biofuels pricing and manufacturing economics," Department of Energy, South Africa, 2013.

[4] A. Pradhan and C. Mbhowa, "Development of biofuels in South Africa: Challenges and opportunities," Renewable and Sustainable Energy Reviews, 39, p. 1089-1100, 2014.

[5] D. Esterhuizen, "Sugar annual – the Republic of South Africa," Global Agricultural Information Network (GAIN), USDA, 2013.

[6] EIA, "International energy statistics," Energy Information Administration, USA, 2013.

[7] DoE, "Synopsis of the final report on: Assessment of the blending value of bio-ethanol with local and imported petrol," Department of Energy, South Africa, 2012.

[8] DoE, "Petroleum products," Department of Energy, Energy Statistics, South Africa, 2017. Retrieved from http://www.energy.gov.za/ on April 1, 2017.

[9] D. S. Shrestha and A. Pradhan, "Energy life cycle analysis of a biofuel production system," Bioenergy and Biofuel from Biowastes and Biomass, Chapter 18, American Society of Civil Engineers, 2010.

[10] M. Wang, J. Han, J. B. Dunn, H. Cai and A. Elgowainy, "Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use," Environ. Res. Lett., 7 (4), 2012.

[11] I. C. Macedo, M. R. L. V. Leal and J. E. A. R. da Silva, "Assessment of greenhouse gas emissions in the production of and use of fuel ethanol in Brazil," Sao Paulo, Brazil, 2004.

[12] D. Khatiwada and S. Silveira, "Net energy balance of molasses based ethanol: The case of Nepal," Renewable and Sustainable Energy Review, 13, p. 2515-2524, 2009.

[13] D. Khatiwada and S. Silveira, "Greenhouse gas balances of molasses based ethanol in Nepal," Journal of Cleaner Production, 19, p. 1471-1485, 2011.

[14] DoE, "Update on the biofuels industrial strategy," Department of Energy, Souht Africa, 2012.

[15] SASA., "SA Sugar Industry - Facts and Figures," South African Sugar Association, 2014.

[16] L. Mashoko, C. Mbohwa and V. M. Thomas, "LCA of the South African sugar industry," Journal of Environmental Planning and Management, 53 (6), p. 793-807, 2010.

[17] E. Theka, “A life cycle assessment of ethanol produced from sugarcane molasses,” MSc Thesis, University of Cape Town, 2003.

[18] H. Shapouri, M. Salassi and J. N. Fairbanks, “The economic feasibility of ethanol production from sugar in the United States,” Office of Energy Policy and New Uses, Office of the Chief Economist, United States Department of Agriculture and Louisiana Stat e University, 2006.

[19] ANL, “GREET model V1.8d.1,” Argonne National Laboratory, Argonne, IL, USA, 2010.

[20] EPA, “Lifecycle greenhouse gas (GHG) impacts calculations,” EPA-HQ-OAR-2005-0161-3174.10, U.S. Environmental Protection Agency, Washington DC, 2010.

[21] H. Von Blottnitz, E. Theka and T. Botha, T., “Bio-ethanol as octane enhancing fuel additive in Southern Africa: An examination of its environmental friendliness from a life cycle perspective,” National Association for Clean Air Annual Conf., October, Durban, 2002.

[22] L. Moshoko, C. Mhowa and V. M. Thomas, “Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry,” Journal of Cleaner Production, 39, P. 42-49, 2013.