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Synthesis of South Africa’s Biomass to Bioethanol Supply Network

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South Africa produces synthetic ethanol and to date there are no commercial bioethanol production plants in operation in the country. Sugarcane, as well as residues from sugarcane, maize, sorghum, wheat and barley are among the acceptable bioethanol feedstocks in South Africa. As the feedstock cultivation areas are scattered over a wide geographical land area, and the potential bioethanol feedstocks have low energy density, there is a need to locate the processing facilities in strategic positions such that production and logistic costs and greenhouse gas (GHG) emissions due to transportation are minimized. To address the above mentioned challenges associated with bioethanol production in South Africa, a mathematical programming approach for the synthesis of optimal bioethanol supply network is developed. It accounts for sugar demands, production of bioenergy (ethanol, electricity and heat) and other byproducts, various feedstocks and their geographical distributions, etc. Various processing technologies for ethanol production are considered and two data sources for availabilities of feedstocks are used. Synthesis is performed by maximizing the economic objective, measured by annual profit. Evaluation of greenhouse gas (GHG) emissions is also performed. Based on the results obtained, it would be possible, in terms of economics, to meet and surpass the 2 % target penetration of biofuel into the South African national liquid fuel supply stipulated by the government.

1. Introduction

Biofuels which are produced from plants (non-food crops) and agricultural wastes are considered to be among the promising alternatives for the petroleum based fuels used in the transportation sector (Gupta and Verma, 2015). The use of food crops as a source for biofuels results in higher food prices (Chakravorty et al., 2016) and therefore there is a need to develop second generation techniques for bioenergy production (Dias et al., 2014). However, the use of second generation technologies in isolation might not be financially viable, hence it has been suggested that they should be integrated with first generation technologies (Akgul et al., 2012). The two main types of biofuels produced are bioethanol and biodiesel which are blended into gasoline and diesel. In 2015, biofuel production amounted globally to a total of 74.8 × 10^6 t of oil equivalent, with USA contributing 41.4 % while Brazil contributed 23.6 % (BP, 2016). In South Africa, bioethanol production is identified as a source of economic and social development for under-developed areas of the country (DME, 2007). The biofuel industry worldwide, however, faces a lot of challenges which compromises issue of economic viability and commercialisation, especially where lignocellulosic biomass is to be used for production (Singhvi et al., 2014). These challenges include the uncertainty of discontinuous availability of biomass, fluctuations in market prices, high logistic and maintenance costs, etc. The high logistic costs arise from the low energy density of the feedstock as well as its distribution which is usually scattered over a wide area (Delivand et al., 2015). To overcome these challenges an optimised supply chain network is required.

Supply chain networks usually comprise the four major components referred to as nodes in this work, such as farms, collection and pre-processing facilities, processing facilities and refining/blending facilities (You et al., 2012). The focus of this work is to determine the optimal supply network for bioethanol and other byproducts

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in terms of maximal profit and environmental impacts (measured by GHG emissions) associated with bioethanol production.

The problem statement for this study is as follows: Given different kinds of biomass, a set of biomass cultivation sites, a set of pre-treatment and processing facilities locations, a set of sugar mills, a set of blending facilities locations, and a set of pre-treatment and processing technologies. Several variables are determined from the model, such as the sizes and locations of each processing facility, feedstock locations, as well as types and quantities, which are to be shipped to each processing facility to make the supply chain profitable. Furthermore, other parameters to be determined in the supply chain are processing facilities that supply each ethanol demand centre, the quantities of ethanol to be supplied and GHG emissions originating from the supply network.

The novelties of this work are: superstructure of alternatives suitable to South Africa by considering the current production of sugar; the development of the five-layer model enabling co-producing of bioethanol, sugar and other byproducts and two sets of land cover data from two sources for the purpose of comparison.

2. Methodology

A superstructure represented as a mixed integer linear program (MILP) was developed. The superstructure comprises four nodes namely farms, pre-treatment, processing, blending and storage facilities. The pre-treatment, storage and processing facility nodes are split into three resulting in a superstructure with five nodes/layers as shown in Figure 1.

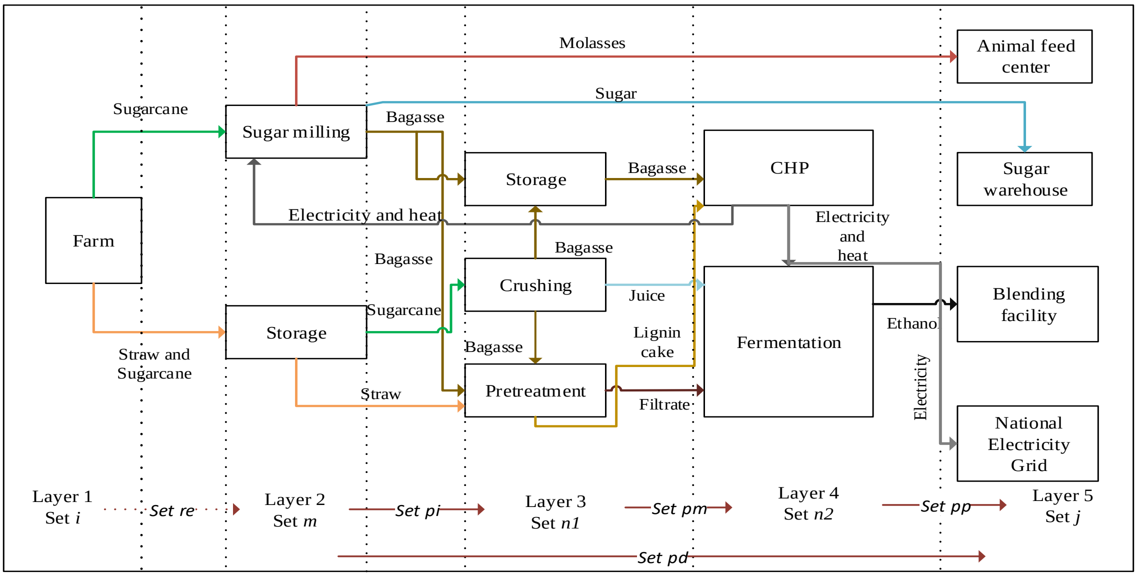

Figure 1: Material flow in the bioethanol and sugar supply network

Each farm has the potential to supply feedstock to any processing facility, and the blending facilities can each receive ethanol from any of the processing facilities. The activities in the supply chain are addressed according to the layers shown in Figure 1 and are described below. The model includes mass balances for each layer, production constraints, economics and environmental impact evaluation. The production constraints include the limit on farm capacities and plant sizes. The model was applied to a South African case study and was solved using the CPLEX solver in the GAMS modelling environment (GAMS, 2016).

2.1 Five-Layer Superstructure of the Supply Chain Network

Layer 1 to Layer 2: After harvesting, feedstocks (sugarcane and residues from sugarcane, maize, sorghum, wheat and barley) are collected from the farms in Layer 1, and transported to storage sites or sugar milling (existing sites) located in Layer 2. The maximum amounts and types of biomass that can be collected from the farms are constrained by the farm production capacities and the biomass production rates at the farms.

Layer 2 to Layer 3: Bagasse, byproduct from sugar milling is sent to storage for further processing. Feedstocks from storage from Layer 2 are transported to technologies in Layer 3. Straw is sent to pre-treatment using acid hydrolysis, and sugarcane which is not used for sugar production is crushed to obtain juice and bagasse. Bagasse is a lignocellulosic material and should also be pre-treated for use in the ethanol fermentation processes. On the other hand, bagasse could be burned in cogeneration plant (CHP) where heat and electricity could be produced and used for the sugar milling and fermentation processes.

Layer 2 to Layer 5: Products that require no further processing are transported to warehouses in Layer 5. These are byproducts and intermediate products from sugar milling, sugar and molasses, and are considered as direct products.

Layer 3 to Layer 4: The filtrate and juice from the pre-treatment stage in Layer 3 are directed to fermentation technology in Layer 4 where they are converted into bioethanol. The filter cake (lignin cake) is to be dried and burned together with bagasse in CHP technology to produce heat and electricity.

Layer 4 to Layer 5: Products and byproducts from the technologies in Layer 4, CHP and fermentation, are transported to demand centres in Layer 5. Electricity produced is used in the processing facilities and sugar mills, and if produced in excess, is sold to the national grid.

It should be noted that recycle is not included in this model directly, but a monetary value equivalent to the value of heat and electricity which can be obtained from the use of lignocellulosic materials (lignin cake, bagasse) is assigned to those materials.

2.2 Economic Objective and Environmental Impact Assessment

Economic objective: Eq(1) shows the economic objective function which is measured by profit before tax:

$$\textit{Profit before tax} = \textit{Revenue} - \textit{Production costs} - \textit{Transportation costs} - \textit{Annualized capital costs} \qquad (1)$$

Sales revenue comprises income from the sale of all products and byproducts which include bioethanol, sugar, molasses, heat and electricity. The production costs include operating costs and feedstock costs. Transportation costs consist of distance fixed cost (cost of loading and unloading) and distance variable cost. Capital costs are calculated based on sixth-tenth rule, and linearized by piecewise linear approximation in order to keep the model linear (Čuček et al., 2014).

Environmental impact assessment: The environmental impact (EI) of the study measured by GHG emissions is calculated according to Eq(2) and comprises environmental impacts due to cultivation of feedstocks, pre-processing and processing, and transportations.

$$\textit{Total EI} = EI_{\textit{feedstock production}} + EI_{\textit{conversion}} + EI_{\textit{transportation}} \qquad (2)$$

Environmental impact assessment of the emissions produced in the supply network is executed using CML-IA baseline method in SimaPro (Classroom, version 8.0.4.30) (PRé Consultants, 2016). The Ecoinvent 3.1 database (Ecoinvent Centre, 2016) was used to obtain most of the data for environmental impact analysis. In cases when the data was not available in this database, the Agri-footprint database (Agri-footprint gouda, 2016) was used. “Well to wheel” life cycle analysis (LCA) boundaries were used in the case study.

3. Case Study

Synthesis of optimal supply network producing bioenergy, sugar and other byproducts was applied to three provinces in South Africa which are, KwaZulu-Natal (KZN), Mpumalanga and the Eastern Cape, see Figure 2. Feedstocks namely sugarcane, and residues from sugarcane, maize, sorghum and wheat are currently mainly produced in those three provinces. Base map in Figure 2 is taken from SANSA (2011), grains shapefiles from DAFF (2014) and sugarcane shapefiles from SASRI (2014) and Ezemvelo KZN wildlife (2013).

For data collection and analysis geographical information systems (GIS) software ArcGIS (Esri, 2016), using a fishnet approach (ISO 19131, 2013) was used to establish the quantities of feedstock available in each location. A grid with cells measuring 30 km by 40 km is considered. Land cover data from two sources was used in this study for the purpose of comparison, giving rise to two sets of data that are referred to as Case 1 and Case 2. The differences between the two cases are: i) maximum capacities of feedstocksin Case 1 are higher than those of Case 2 by 11.4 %., and ii) in Case 2 when compared with Case 1, additional potential sugarcane producing areas are included, besides those areas currently used for the purpose of sugar production. Google Earth® software was used to find the actual transportation distances between locations in the superstructure/supply network, using existing infrastructure.

MILP models consist of approximately 150,000 constraints, 184,000 single variables and 1,220 binary variables and was solved in about 300 s on a personal computer with an Intel® Core™ i3-5005U processor with 4 GB of RAM.

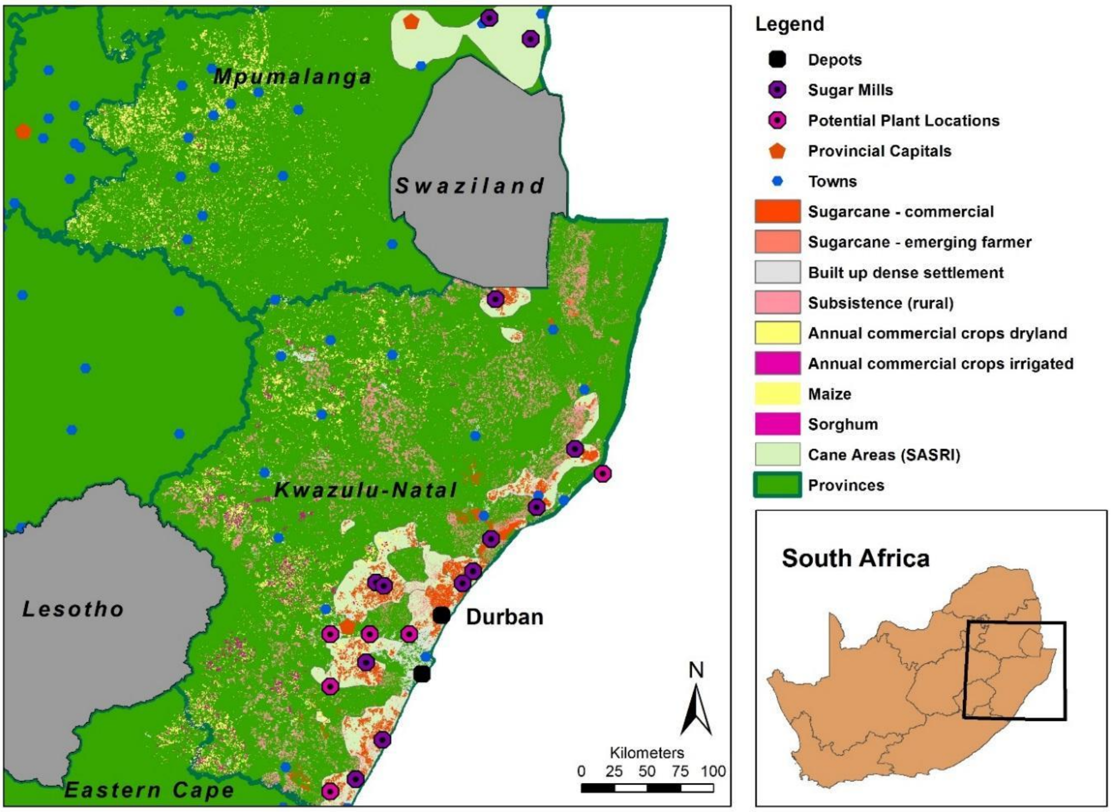

Figure 2: Area in South Africa under study including some details regarding supply network

4. Results and Discussion

4.1 Profitability Analysis

The optimised model for Case 1 has optimal profit of 2,174.3 × 10^6 ZAR/y (South African Rand/y) and for Case 2 optimal profit is 12,748.7 × 10^6 ZAR/y, see also Table 1. In the first case 0.641×10^6 t/y of ethanol is produced with maximum plant capacity of 65,520 t/y from 15 plants selected, while in the second case 3.135 × 10^6 t/y of ethanol is produced in 28 plants with maximum capacity of 233,746 t/y of ethanol. The model in both cases, had only sugarcane and bagasse being selected as feedstocks for bioethanol production. In Case 1 a very small percentage (541.5 t/y or 0.08 %) of bioethanol was produced from sugarcane due to the size of the cultivation area of the current sugar mill supply areas. On the other hand, around 72.6 % of bioethanol was produced in Case 2 from sugarcane, and around 27.4 % from bagasse. In both cases the demand for sugar (2.44 × 10^6 t/y) was just satisfied, from which it can be concluded that production of bioethanol is more profitable than production of sugar.

4.2 Environmental Impact Assessment

Environmental impact is assessed in terms of GHG emissions. The overall GHG emissions originating from the optimal supply network for Case 1 amounts to 3.74 × 10^6 t $CO_{2\text{-eq}}$/y, and for Case 2 to 6.75 × 10^6 t $CO_{2\text{-eq}}$/y. The main differences between the results are due to more than double consumption of sugarcane in Case 2, and consequently larger amounts of bioethanol produced, see also Table 1. The processing stage contributed the most to the overall environmental impact (57.7 % in Case 1 and 51.6 % in Case 2) followed by feedstock production which contributed 24.8 % in Case 1 and 31.8 % in Case 2. The difference between the cases is due to higher consumption of sugarcane in Case 2, and therefore there is higher share of GHG emissions for feedstock production. Transportation had the least environmental impact constituting about 17 % of the total environmental impact of the supply chain network for both cases.

4.3 Sensitivity Analysis

Sensitivity analysis was done by varying the parameters, such as product prices, transportation costs, sugar demand and feedstock costs. All the parameters were increased by 20 % from the base case. The main results of sensitivity analysis are shown in Table 1 where only specific parameter was increased at a time, while all the others remained as in base case.

Table 1: Main results from sensitivity analysis

	Base case	Product prices	Transportation costs	Sugar demand	Feedstock prices
Case 1					
Annual profit (MZAR/y)	2,174.3	6,890.8	201.6	Infeasible	157.4
Payback period* (y)	5.47	2.31	13.0		13.4
Raw material used (Mt/y)					
- sugar cane	25.73	25.73	25.73		25.73
- bagasse	6.84	6.84	6.84		6.84
Revenue (MZAR/y)	23,582.4	28,298.8	23,582.4		23,582.4
Total annual cost (MZAR/y)	21,408.1	21,408.1	23,380.7		23,425.0
Transportation cost (MZAR/y)	9,863.4	9,863.4	11,836.0		9,863.4
Produced main products (Mt/y)					
- sugar	2.44	2.44	2.44		2.44
- ethanol | demand (%)**	0.64 | 4.8	0.64 | 4.8	0.64 | 4.8		0.64 | 4.8
GHG emissions (Mt CO$_{2\text{-eq}}$/y)	3.74	3.74	3.74		3.74
Case 2					
Annual profit (MZAR/y)	12,748.7	25,983.0	8,141.5	12,165.6	8,315.8
Payback period* (y)	2.69	1.48	3.48	2.69	3.47
Raw material used (Mt/y)					
- sugar cane	59.45	61.04	51.40	60.99	52.08
- bagasse	15.8	16.23	13.67	16.22	13.85
Revenue (MZAR/y)	65,124.6	80,099.0	56,144.6	64,591.9	57,139.7
Total annual cost (MZAR/y)	52,375.9	54,116.0	48,003.0	52,426.3	48,823.9
Transportation cost (MZAR/y)	25,809.2	26,868.3	24,972.6	25,404.2	21,395.2
Produced main products (Mt/y)					
- sugar	2.44	2.44	2.44	2.93	2.44
- ethanol | demand (%)**	3.14 | 23.6	3.23 | 24.3	2.62 | 19.7	2.93 | 22.0	2.68 | 20.2
GHG emissions (Mt CO$_{2\text{-eq}}$/y)	6.75	6.92	5.92	7.06	6.02

MZAR/y - $1\cdot10^6$ ZAR/y, Mt/y - $1\cdot10^6$ t/y

*It has been assumed that no investment in sugar mills, cogeneration facilities, infrastructure and vehicles

**Demand for gasoline in South Africa is approximately 8.26 Mt/y (Department of Energy South Africa, 2016)

From Table 1 it can be seen that much larger differences are obtained in Case 2 than in Case 1. In all cases the annual profit was positive, and is most significant when product prices were increased. All the solutions provide the same amount of sugar produced (based on its demand), except when increasing sugar demand. In Case 1 it is not possible to increase sugar demand, as Case 1 includes only those areas currently used for the purpose of sugar production. On the other hand, in Case 2 it is possible to increase sugar demand, as Case 2 additionally considers potential sugarcane producing areas. From Table 1 it can also be seen that an increase in transportation costs has the greatest negative impact on the profitability of the supply network, followed by changes in feedstock purchase prices. In both cases more that 2 % of gasoline demand can be satisfied by ethanol, in Case 1 the value is slightly lower than 5 %, while in Case 2 is between 19.7 % and 24.3 %.

5. Conclusions

The results show that in addition to feedstock costs, transportation costs constituted a large part of the total costs of the supply chain and was part of the issues identified with the commercialisation of bio-ethanol processing in South Africa. Reducing the cost of transportation and/or reducing the transportation distances of biomass by way of locating processing facilities closer to the biomass sources could make the bioethanol industry more economically beneficial. The results also confirmed that use of residue material that requires no transportation was profitable in bioethanol production.

According to the analysis, the biomass to bioethanol supply chain for the case study considered is economically viable and could meet the 2 % target demand of blending bioethanol into the national liquid fuel supply. However, increasing transport and feedstock prices rendered the model less profitable. All the plants in Case 1 could also qualify for government incentive, which would reduce the overall cost of the bioethanol supply chain.

From the environmental analysis, it could be concluded that feedstock processing contributed the most to the overall environmental impact of the supply chain. Transportation, especially feedstock transportation, also contributed significantly to overall GHG emissions and efforts should be directed to building processing facilities closer to the feedstock sources in order to reduce the biomass transportation distances, so that the operation can be both environmentally and economically favourable.

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