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BIO-ETHANOL FOR SUSTAINABLE DEVELOPMENT: THE CASE OF SUGAR CANE IN MAURITIUS

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ABSTRACT

Bio-ethanol is being promoted worldwide to reduce the transportation sector's reliance on fossil fuels and to lessen greenhouse gas emissions. However, it may lower fossil fuel and contribute to a low carbon energy source if the entire production system is able to offer net energy gain and net carbon savings at a reasonable cost. This study assesses the production pathway of molasses-based ethanol in Mauritius in terms of three indicators: energy yield, carbon emission avoided and the life-cycle cost accounting. The specificity of the production pathway involves co-products besides ethanol. Through an inventory of inputs used in the preparing feedstock and the conversion technology, the findings indicate an energy yield of 9.30 MJ and 1.4kg of carbon emission avoided per litre of ethanol. The life-cycle cost accounting shows that it costs the production system Rs1.06 to produce 1 MJ of ethanol while it costs Rs0.68 to acquire 1MJ of gasoline. While it may not be cost effective to produce ethanol, by taking into account the carbon emission avoided and its associated social cost, ethanol becomes environmentally more cost-effective than gasoline. A sensitivity analysis reveals that fertilisers, transportation of feedstock and electricity influence energy and carbon indicators. Using a gasoline demand equation, the equivalent displaced fossil fuel from ethanol can be achieved by a rise in gasoline price by 34%.

Key words: bio-ethanol, molasses-based ethanol, energy balance, energy yield, carbon emission avoided, life-cycle cost assessment

JEL: Q01, Q15, Q42, Q48

ACRONYMS	
CCS	Carbon Capture and Storage
CO2	Carbon Emission
ER	Energy Yield
GHGs	Greenhouse gases
LCC	Life - Cycle Cost
LHV	Lower Heating Value
MAAS	Multi-Annual Adaptation Strategy
MJ	Megajoules
MOE	Molasses-based Ethanol
NEB	Net Energy Balance
NRnEB	Net Renewable Energy Balance

1. Introduction

Bio-ethanol, derived from biomass, is being promoted worldwide because its use may reduce the transportation sector's reliance on fossil fuels, and may potentially lessen greenhouse gas (GHG) emissions (Blottnitz and Curran, 2007; Sims *et al*., 2010; Wang *et al*., 2011). It is produced through the fermentation of agricultural products such as sugarcane, molasses, corn, wheat and sugar beet, among others and is a form of renewable energy (Goldemberg *et al*. 2008). As a vehicle fuel, ethanol can either be blended with gasoline, typically 5 to 20% by volume, for use in existing vehicle with no engine modifications or be used in its pure form in vehicles with modified engines (Fu *et a*l., 2003; Amigun *et al*., 2008; Leite *et al*., 2009).

It is generally believed that replacing one litre of gasoline by one litre ethanol will lead to lower fossil fuel consumption and carbon emission (CO2) (Demirbas, 2006; Balat and Balat, 2009). However, there is increasing apprehension about the potential impacts of ethanol development. Ethanol can lead to lower fossil fuel and may be considered as a low carbon energy source if the entire production system is able to offer net energy gain and net carbon savings (Khatiwada and Silveira 2009; Sims *et al*. 2010,). Energy is consumed and CO_2 is produced, not only in the combustion of the ethanol at the point of use but also during feedstock preparation, refining, transportation and final conversion. In this respect, two policy indicators which are associated with ethanol production are its net energy balance (NEB) or net renewable energy balance (NenEB) and the net carbon emission avoided (Prakash *et al*. 1998; Gopal and Kammen 2009; Nguyen et al. 2007). Energy balance is defined as the difference between the energy content from ethanol and the energy used in its production (Henke *et a*l. 2005; Nguyen et al. 2007).

Biofuel systems, including the preparation of feedstock and the conversion of feedstock to ethanol, involve production and processing costs which depend on production pathways. Production costs depend on the location, design and management of the installation, and on whether the facility is an autonomous distillery in a cane plantation dedicated to alcohol production, or a distillery annexed to a plantation primarily engaged in production of sugar for export (Amigun *et al*. 2008). If biofuels represent a small improvement in the net energy balance, but a huge increase in cost in relation to alternative options, then it is less likely to offer a cost-effective means of achieving the goal of a low carbon economy. In fact, the high costs involved in certain countries often require government subsidies in order for them to compete with petroleum products and this has led to greater scrutiny on whether ethanol is a viable option for energy security and to mitigate GHGs (Sims *et al*. 2010). Thus, the life-cycle cost assessment of ethanol production system is another indicator which assists in policy making (Wang *et al*. 2011). Studies such as Zhang *et al*. (2003), Hu *et al*. (2004) and Restianti and Gheewala (2012) have integrated life-cycle cost assessment in their ethanol production assessment.

According to Wang *et al*. (2011), the production pathways of ethanol, the characteristics of feedstock, conversion technologies, among other factors, have important implications on energy balance, CO2 emissions and cost of producing ethanol. Recently there has been a growing interest to assess the energy and environmental costs and benefits of ethanol production from molasses – a co-product of sugar production (Gopal and Kammen 2009, Khatiwada and Silveira 209, Nguyen and Hermansen 2012). This study assesses the production of ethanol from molasses from an economic perspective for a small island state, Mauritius. Three indicators for sustainable energy resource systems are calculated: the net energy balance, the net carbon emission savings and the life-cycle cost (LCC) of producing ethanol. Based on these indicators, the cost associated with the net energy gained and carbon emission avoided from ethanol is compared with the cost of acquiring conventional gasoline. The analysis also shows the cost effective strategy when the social cost of carbon is accounted in the calculation.

A specificity of the Mauritian molasses-based ethanol is that there are multiple products associated with the production pathway. The production system produces sugar and molasses as final products and hence, a method is needed to distribute energy and carbon emission among co-products. An economic-based value method is used as the apportionment rule in this respect. This method distributes energy and CO2 emission according to the economic value of co-products. This rule has implication on the conclusion and a section is devoted to analyse the uncertainties of economic value of co-products on energy and carbon assessment.

The study is structured as follows: Section 2 defines the terminology which is used in this study including concepts such as net energy balance, energy yield and CO2 avoided, among others. Section 3 provides a brief review of literature on energy balance and CO2 emission of ethanol production pathways. This is followed by section 4 which gives an overview of the Mauritian Sugar Industry and section 5 which develops the conceptual framework and explains the methodological issues involved in the assessment of molasses-based ethanol in Mauritius. Section 6 shows the findings of the study – net energy balance, carbon emission avoided and life- cycle assessment and section 7 provides a discussion of the findings and illustrates the sensitivity parameters of the analysis. Section 7 also gives the sensitivity of the estimates to changes in the production inputs and in the apportionment ratio. A simulation exercise was undertaken using @Risk decision tool software to show the variations of the findings associated with uncertainties in economic value of co-products. A cost and benefit analysis is also presented in this section. Section 8 concludes with avenues for future research.

2. Definition of the terminology

The terms which are used in this paper have been defined in many ways over the years (Hammerschlag, 2006). It is therefore critical that the reader understands exactly how these terms are defined and used here. Following related studies in this field, all energy values are reported in units of Megajoules (MJ) and carbon emission is measured in kg.

Net Energy Balance (NEB), Net Renewable Energy Balance (NRnEB) and Energy yield ratio (ER): Net *e*nergy balance is defined as the difference between the energy content of ethanol and the total energy inputs in the fuel production cycle (Levelton, 2000; Shapouri *et al.*, 2004; Macedo *et al.*, 2004). In assessing ethanol's energy performance, net energy value is a key indicator to identify the gain or loss of energy from the production of ethanol. It weighs the energy content of ethanol against the energy inputs in the fuel production cycle. More specifically there are three ways in which energy in relation to ethanol is being addressed (Nguyen *et al.* 2008, Khatiwada and Silveira 2009). The first one defines net energy value as follows:

Net energy Balance or Value (NEB) = Energy content of Ethanol-Net Energy Inputs (total fossil and non-fossil energy inputs, excluding energy recovered from system co-products, for example biogas).

Though energy performance is conventionally considered using the NEB, it may be more appropriate to evaluate a biofuel's contribution to fossil energy use reduction. Such an evaluation addresses how much energy is gained when the non-renewable fossil fuel energy is expended to produce renewable biofuel such as ethanol. The equation of the net renewable energy balance is thus

Net Renewable Energy Balance (NRnEB) = Energy content of Ethanol-Fossil Energy Inputs

Energy ratio or energy yield is another indicator which is defined as follows:

Energy Ratio (ER) = Energy in a litre of ethanol /non-renewable energy required to produced a litre of ethanol.

Carbon emission avoided: Avoided emissions relate to the use of biomass consumed as fuel which replaces a quantity of fossil fuel that may have been used, or improved efficiency in energy utilisation and this leads to a fall in fossil fuel use. The CO2 that may have resulted from its combustion is classified as avoided emission (Blottnitz and Curran 2007).

Higher vs Lower Heating Values: A litre of gasoline contains 36.1 MJ of energy. However, when carbon-based fuel is burned, the two main combustion products are carbon dioxide (CO_2) and water vapour and some heat released is not perceivable as temperature but is used in vaporising the water during combustion. Energy analysts exclude this relatively useless latent heat and report the Lower heating Value (LHV) for fuels which is 32MJ for gasoline (Hammerschlag 2006). Similarly, a litre of ethanol contains 23.6MJ of energy and the LHV is 21.2MJ for ethanol. The LHV is used in this study.

Functional unit: A functional unit is a measure of the performance of a system (Garcia *et al.* 2011). The functional unit is 1 tonne of sugar. Energy is measured in Megajoules (MJ) and carbon emission (CO2) is measured in g or kg.

3. A Brief review of literature on energy balance, energy yield and carbon emission

Energy assessment for bio-ethanol

Giampietro *et al.* (1997) rated sugarcane as the best performing commercial bioethanol production input. Net life-cycle energy balances of bioethnaol from sugarcane are generally agreed to be positive (Blottnitz and Curran, 2007; Botha and Blottnitz, 2006; Macedo, 1998; Prakash *et al.*, 1998; Oliveira *et al.,* 2005). The Brazilian ethanol programme is widely considered as one of the most energy and land efficient commercial bioethanol production systems on a environmental life-cycle basis (Giampietro *et al.*, 1997; Blottnitz and Curran 2007; Cortez *et al.*, 2003). Commercial scale sugarcane production is estimated to store up to 400 GJ energy equivalents per hectare each year (IPCC, 2001; Sims, 2004). Relatively low input bioethanol production systems (such as in Brazil) are estimated to have an output to input energy ratio of three to one; energy output in Brazil is estimated to be on average 9.2 MJ/tonne of cane (Macedo, 1998). The positive energy output result is not unanimous as it is also argued that Brazil's net energy balance is negative in some instances (Pimentel, 2001). It is widely agreed however that efficiencies have improved over time due to developments in technology and production (Niven, 2005; Oliveira *et al.*, 2005). Brazilian ethanol yields have improved in part through development of plant strains with higher proportions of total sugars (Kheshgi *et al.*, 2000). Overall, many systems operate well below maximum levels of environmental efficiency (Borrero *et al.*, 2003).

More recent studies namely Nguyen *et al.* (2008) carried out a full chain energy analysis of fuel ethanol from cane molasses in Thailand. The molasses-based ethanol system involves three main segments which are cane cultivation, molasses generation and ethanol conversion. In sugarcane farming, energy inputs in fertilizer and herbicide manufacture has the largest share as it consists of 45.6 percent of the total energy inputs. The energy input associated with one tonne of cane reaching the sugar mill gate amounts to 465.4MJ and the net energy input in sugar milling amounts to 410.2MJ after deducting the amount of energy provided by bagasse. The energy inputs associated with one tonne of cane total 706.2 MJ after deducting the electricity output from sugar milling of 169.4MJ. 10.4 percent of the energy used in sugar cane farming and milling are allocated to molasses. Among the subs-systems of molasses-based ethanol production cycle, ethanol, conversion is the most energy consuming component with 63.9 percent, followed by molasses generation 14.6 percent, sugar cane farming 13.5 percent, and transportation 8 percent. Given the conversion rate of 225 L molasses-based ethanol per tonne molasses or 10.17 L per tonne of cane, the production of ethanol can result in net renewable energy gain of 5.95 MJ/L.

A similar study was undertaken by Prakash *et al.* (2008) for India. The system boundary included only ethanol conversion phase. The energy consumed for the process is derived from bagasse and biogas recovered from stillage. Subtracting the amount of energy from biogas (11.27 MJ/L) from the total process energy consumption, 21.1 MJ/L, gives a net energy input of 9.83 MJ/L. Thus, a positive NRnEB of 11.37 MJ/L (21.2–9.83) was evaluated.

Khatiwada and Silveira (2009) evaluated the life-cycle energy analysis of molasses-based ethanol in Nepal. They used net energy balance, net renewable energy balance and energy yield ratio to evaluate the energy balance of MOE in Nepal. Total energy requirements in sugarcane farming, cane milling and ethanol conversion processes are estimated and energy is distributed between co-products (molasses and sugar) as per their market prices. The sum of the primary energy requirements in the different processes of the plant gives total energy demand of 7355.8 GJ/day. Bagasse and biogas account for the plant's energy supply. Sugar milling process consumes a large amount of primary energy (73 percent), and fermentation/distillation and dehydration only take 4 percent and 2 percent respectively. Fermentation/distillation consumes 12.6 MJ/ L, followed by sugar milling which consumes 10.5 MJ/L (Khatiwada and Silveira, 2009). Considering the energy content of anhydrous ethanol aimed as transport fuel, the value of 21.2 MJ/L (lower heating value) attained shows that the NRnEB is positive (18.36 MJ/L) but the NEB is negative (-13.05) and energy yield ratio (7.47). The high positive value of NRnEV and energy yield ratio reveal that a low amount of fossil fuels are required to produce 1 L of MOE. However, negative NEB reveals that the total energy consumption (both fossil and renewable) to produce the ethanol is higher than its final energy content. Nevertheless, the renewable energy contribution amounts to 91.7 percent of total energy requirements. The effect of the increased price of molasses and reduced energy consumption in the sugarcane milling and ethanol conversion are found to be significant in determining the energy values and yield ratio of MOE.

Carbon emission and ethanol production system

Emissions are produced through energy and inputs used throughout the bioethanol lifecycle. Biofuels are produced from biomass, which can be considered a closed loop carbon system- that is a system whereby recovery, re-use or recycling of resources is promoted. For example, energy that would conventionally be wasted often can be recovered and reused. However, emissions from inputs throughout the production cycle create net GHG emissions (Demirbas, 2001). GHG emissions are understood as net life cycle GHG emissions per unit, and also avoided emissions per unit relative to petrol. Sustainable production of high yield biomass, efficient product conversion and use, and suitability low levels of renewable inputs will maximize emissions reductions (Larson, 2005).

Figures of emissions produced or reduced vary dependent upon the system and the method of calculation (Blottnitz and Curran, 2007). In the literature, there are large variations in GHG balances of sugarcane ethanol systems (Larson, 2005; IEA, 2004). Throughout the life-cycle, agricultural production has the greatest associated GHG emissions, largely associated with nutrient inputs, but also crop burning and mechanization (Macedo, 1998; Ramjaewon, 2004). Methane and nitrogen dioxide can also occur through poor management of stillage and nitrogen fertiliser applications (Macedo, 1998). During fermentation, approximately 0.76 kg of CO_2 is emitted for each litre of ethanol produced (Kheshgi and Prince, 2005). Transportation of crops and products also increases the GHG emissions associated with each unit of bioethanol produced.

Kheshgi and Prince (2005) estimated full fuel cycle CO_2 emissions of Brazilian ethanol (including crop and fuel production and transportation) to be 1.25 Mg CO_2/ha/yr (based on a reasonable 5170 l yield per hectare). Well-to-wheels CO_2 equivalent emissions estimates are 0.20 kg/l of ethanol (compared to 2.82 kg/litre of petrol) (IEA, 2004). In evaluation of biofuels life cycle impacts, it is also important to consider alternatives for land use- not only in terms of sustainability in general but also in terms of GHG reduction efficiencies per land area (Larson 2005; Moreira and Goldemburg, 1999; IEA, 2004). It is estimated that plantations may store approximately 180 tonnes of carbon/hectare over a century, whereas Brazil's ethanol production may be approaching 330 tC/ha over the same time period (Moreira and Goldemburg, 1999). Given available land areas, population growth rate and consumption behaviour, the main overall limiting factor to biofuels development will ultimately be land availability. Emission reductions through biofuel substitution may be less than expected if fossil fuel displacement is not in a 1:1 ratio and biofuels merely provide a new energy source to meet growing demand – this highlights the need for complementary energy demand and fuel efficiency initiatives (Schlamadinger *et al*., 1997).

Sequestration of carbon emissions in production is also suggested as a future option for emissions reduction (Larson, 2005; Kheshgi and Prince, 2005; Mollersten *et al.*, 2003). In fact, carbon sequestration involves the capture and storage of carbon dioxide that would otherwise be present in the atmosphere, contributing to the greenhouse effect. The carbon dioxide is captured either before or after fossil fuel is burned and then be stored or sequestered. Carbon Capture and Storage (CCS) can be feasibly integrated into new, large, CO_2 -producing power plant systems to reduce carbon emissions by 90 percent or more but implementing CCS inevitably increases the cost of coal-fuelled electricity (Metz, 2005).

4. The Mauritian Sugar industry

At the time of independence in 1968, Mauritius inherited from a monocrop economy depending highly on sugar as its main growth sector. In 1972, the sugar industry was the largest employer with 70,000 workers that is 36 percent of the population. Sugar exports amounted to around 45 percent of total exports and 94 percent of visible exports. In the same year, sugar represented one third of GNP. In 1975, Mauritius benefited from the ACP-EU Sugar Protocol where it has a quota of 507,000 tonnes of sugar at a guaranteed price of export to the EU market (Rojid *et al*, 2009). The success of the sugar industry is due to the preferential trade agreements that the country benefited successively from the United Kingdom and from the European Union. The stable revenues from sugar exports served in the diversification of the Mauritian economy, with the expansion of tourism, financial services and manufacturing industries (Zafar, 2011).

In 2003, sugarcane was cultivated on 72 000 hectares, representing 85 percent of the arable land in Mauritius. Around 60 000 persons, one out of every three family in the rural areas, are directly or indirectly involved in the sugar industry. On average, 575 000 tonnes of sugar was produced annually, exports to the EU and the US under preferential arrangements amount to some 540 000 tonnes, whereas some 8000 tonnes of special sugars were sold to 23 world market destinations at world market prices plus a premium. Domestic consumption of sugar was about 40 000 tonnes per year. The bulk of the exports are under the Sugar Protocol (507 000 tonnes), the Special Preferential Sugar Agreement (SPS), (some 20 000 tonnes), while sales to the US under the Global Import Quota represent some 12 000 tonnes. The share of sugar production in the Mauritian economy has consequently over the years and in relative terms dwindled to about 3.5% of the GDP in 2003 (from 25% in the 1970s). Mauritius benefited significantly from preferential access to European markets for the past 50 years. Through the Sugar Protocol and Special Preferential Sugar Agreement the country received guaranteed prices that at some 100–200 percent above world market prices and guaranteed market share through quotas. Between 1975 and 2000 the cumulative benefit to Mauritius from quasi transfers from European consumers amounted to about $3.5 billion (IMF 2002a), or 6.1 percent of GDP.

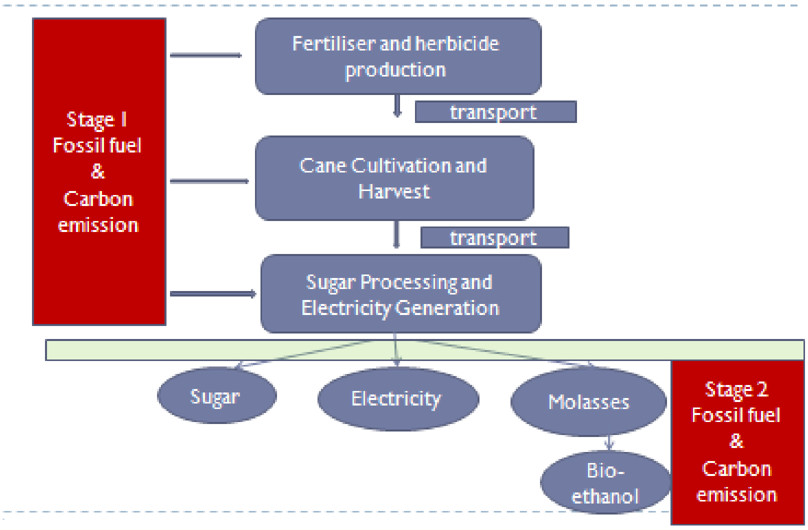
In June 2005, the European Commission calls for severe reductions in EU sugar prices and an end to the current system of national quotas. Under the new EU sugar regime, the EU reference price for both raw and white was reduced by 36 percent by October 2009. As the biggest quota holder under the Sugar Protocol (37 percent), Mauritius is the mostly affected country. It is expected to lose up to €895 million during the nine years of the implementation of the new Sugar Regime and suffer from a direct permanent loss of €95 million annually. The reduction in price in the EU means a shortfall in export earnings of €782 million over the 2006-2015 period. The effective loss to the economy is in fact much higher if the social and environmental multiplier effects of the sugar industry are taken into account.

With the changing global environment and the EU sugar reforms, the Mauritian Government, in consultation and collaboration with stakeholders, devised a multi-annual adaptation strategy in the form of a ten year, 2006-2015, Action Plan. The objective of the MAAS is to ensure the commercial viability and sustainability of the sugar sector for it to continue fulfilling its multi-functional role in the Mauritian economy, but at a significant social cost. The Strategy provides for a set of measures/projects aiming at improving the cost competitiveness of the sugar sector; increasing the country's revenue: increasing the contribution of the sugarcane cluster to national electricity production with the installation of new power plants in the remaining mills, optimising the use of by-products by producing 30 million litres of ethanol from molasses in two of the four remaining sugar factories to be used locally for blending with gasoline; and finally maintaining the social welfare of low income groups of the sugar industry.

5. Conceptual framework and methodological issues

For the purpose of assessing the energy balance and carbon emission of ethanol, it is essential to define the system boundary. In most studies which have conducted Lifecycle Assessment for sugar production or molasses-based ethanol, the main operating units are: sugar cane cultivation and harvest, manufacture of fertilizer and herbicide, transportation and sugar processing and electricity generation (Ramjeawon, 2004; Nguyen *et al*. 2008; Silalertruksa & Gheewala, 2009). Accordingly, the entire input of energy during the complete production chain needs to be estimated. The production processes can be separated into two stages: the production of agricultural energy feedstock and the conversion of this feedstock into ethanol as shown in Figure 1.

Figure 1: System boundary for ethanol production



Source: authors

As can be seen from in figure 1, fossil fuel is combusted and carbon is emitted in stage 1 - the production of feedstock – and eventually, in stage 2 which relates to the conversion of molasses into bio-fuel. Fossil energy inputs during the production of the feedstock result mainly from the energy content of fertilizer and pesticides, the use of agricultural machinery and the energy input for transporting the feedstock. The energy input necessary for both agricultural production and conversion varies between different feedstocks (Blottnitz and Curran, 2007). The system boundary for energy and carbon emission assessment in this study includes the production, transportation and application of fertiliser and herbicide, transportation of feedstock to factory, irrigation, sugar milling and conversion of molasses into ethanol.

5.1 Stage 1: energy and carbon emission in the production of feedstock

Molasses-based ethanol depends on sugar as feedstock. Sugar cane crop rotation covers a two to seven year period followed by one to four ratoons. The representative rotation is taken from cultivation with a seven-year plant cycle (Ramjawon 2004). The steps involved at this stage include land preparation, planting, crop maintenance (through the use of fertiliser, herbicides, watering), and harvesting. Energy which is combusted in each of these processes must be assessed. The following provides an overview of the method which is applied to calculate the energy. The functional unit is amount of megajoules per tonne of sugar.

A. *Energy consumed in fertiliser production*

The inputs in cane cultivation include Nitrogen, Phosphorous and Potassium (NPK) as fertiliser. Thus, energy consumed in the production of NPK, E_f, is estimated in equation (2) as follows:

$$E_f = \frac{f_k.h.f.}{s} \qquad (2)$$

h =amount of hectare for sugar cane cultivation
f = fertiliser (kg) used per hectare
f_k =heat (energy) content (LHV) for producing NPK per kg in MJ
s = tonne of sugar produced

Given that sugar yield per hectare is $y_s = s/h$, equation (2) can be written as follows:

$$E_f = \frac{f_k.f}{y_s} \qquad (2a)$$

Carbon emission, C_f, per tonne of sugar is calculated by taking the carbon emission factor into consideration, f_c, such that

$$C_f = \frac{f_c \cdot f}{y_s} \qquad (3)$$

B. Energy used in herbicide production

Herbicide is the second main input in cane cultivation. The estimated energy consumed in the production of herbicide follows the same method as fertilisers (NPK) and is shown below.

$$E_\eta = \frac{\eta_k \cdot \eta}{y_s} \qquad (4)$$

η = amount of fertiliser used per hectare
η_k =heat (energy) content (LHV) per kg in MJ
y_s =sugar yield per hectare

Carbon emission produced during the production process is given as follows:

$$C_\eta = \frac{\eta_c \cdot f}{y_s} \qquad (5)$$

Where η_c is the carbon emission factor for the production of herbicide.

C. Energy and carbon is transportation of fertiliser and herbicides

The transportation of fertiliser and herbicide from harbour to sugar cane field consumes fossil fuel (diesel) and implies energy being used and carbon emitted during the transportation phase. The energy consumed and carbon emitted are calculated by taking into consideration the average distance travelled from harbour to sugar cane field, the amount of tonne which is transported per trip with the existing carrying capacity of the truck.

Energy consumed is calculated by equation (6):

$$E_{tf} = \frac{d_e d.l_f.f}{load.y_s} \qquad (6)$$

d = amount of diesel consumed per trip

d_e = heat content of diesel

l_f = average distance travelled per trip

y_s =sugar yield per tonne of cane

$load$ =carrying capacity of truck

Carbon emitted during the phase is calculated by taking the emission factor of the combustion of diesel. This is shown in equation (7)

$$C_{tf} = \frac{d_c d.l_f.f}{load.y_s} \qquad (7)$$

Similarly, to estimate the energy consumed during the transportation of herbicides, equation (7) has been adjusted by the amount of herbicide consumed per hectare and the average distance of transportation.

$$E_{t\eta} = \frac{d_e d.l_h.\eta}{load.y_s} \qquad (8)$$

Carbon emission in the transportation of herbicide follows the same reasoning (equation (9)).

$$C_{t\eta} = \frac{d_c d.l_h.\eta}{load.y_s} \qquad (9)$$

D. Transportation of sugar-cane to sugar factory

The transportation of sugar cane to the factory is another segment of the production pathway which consumes energy and emits CO2. Equation (10) and (11) shows the relationship between the different variables which are used to calculate this level of energy and the associated CO2.

$$E_{ts} = \frac{d_e d.l_s.y_{sc}}{load} \qquad (10)$$

$$C_{ts} = \frac{d_c d.l_s.y_{sc}}{load} \qquad (11)$$

y_{sc} = sugar to sugar cane ratio (to produce one tonne of sugar, there is need for y_{sc} tonnes of sugar cane)

l_s = average distance per trip for the transportation of sugar cane to sugar mill.

E. Energy and carbon emission produced from irrigation

Irrigation is a mechanised process and electricity is used in that process which is linked to energy and carbon emission. The amount of electricity consumed, however, depends on the percentage of land irrigated. Thus, equation (12) is derived to account for the percentage of land under irrigation..

$$E_x = \frac{x.x_p x_e}{y_s} \quad (12)$$

x =amount of electricity consumed per hectare

x_p =% of land irrigated

x_e =heat content of 1 KWh of electricity

To estimate carbon emission from irrigation, it is important to consider the type of inputs which are used to generate electricity. Each type of input (fuel oil, coal, diesel etc) will have different emission factor. As will be shown in the following section, fuel oil is used and hence, this paper takes the emission factor of fuel oil into account.

$$C_x = \frac{x.x_c x_e}{y_s} \quad (13)$$

x_c =carbon emission factor (assuming electricity is produced from fuel oil.

F. Energy and carbon in sugar milling

When sugar cane arrives at the sugar mill, it is crushed to extract juice and the water content of the juice is removed in the subsequent heating and evaporation process, leaving a thick concentrated juice. Bagasse is the main energy source for sugar mill. The energy consumed, E_m, in this process is estimated as follows:

$$E_m = x_m x_e y_{sc} \quad (14)$$

x_m =electricity (KWh) used per tonne of sugar cane

Carbon emission is calculated as follows;

$$C_m = x_m x_c y_{sc} \quad (15)$$

Since bagasse is used for electricity generation, the last component is usually ignored.

5.2. Stage 2: energy and carbon emission in ethanol conversion

Ethanol can be produced in two forms: hydrous and anhydrous (Amigun *et al*. 2008). Hydrous ethanol typically has purity of about 95% plus 5% water. This can be used as a pure form of fuel in specially modified vehicles. Anhydrous alcohol (water-free or ''absolute'') on the other hand is formed when the last traces of water are removed. Anhydrous ethanol requires a second stage process to produce high-purity ethanol for use in petrol blends; in effect, the 95% pure product is dehydrated using Azeotropic processes or a molecular sieve to remove the water, resulting in 99% pure alcohol. The energy used in ethanol conversion relates to the electricity used by the machinery.

5.3. Life cycle cost assessment

The life cycle cost of producing ethanol using molasses from sugarcane as feedstock is worked out from Professor William Jaeger work book (2008). Zhang *et al.* (2003) include the purchase of vehicles, the refuelling of infrastructure and the operation and maintenance and repair of vehicles in their life cycle cost assessment. For this study, based on the system boundary, costs which are incurred in stage 1 and stage 2 are calculated. For feedstock production (stage 1), the cost stages include ground preparation, seeding and seed, fertiliser and applications, chemicals and applications, water and applications, harvest, labour and land preparation. In stage 2, the cost of conversion of molasses to ethanol is estimated and added to the cost in stage 1. This method is also applied by Zhang *et al*. (2003), Hu *et al*. (2004) and Restianti and Gheewala (2012).

5.4. Apportionment rule of multiple products pathway

In most biofuel production pathways, products besides biofuels are generated. There are five potential methods to address multiple products of biofuel production pathways (Wang *et al*. 2011). The products have significant commercial value and are part of the value chain of biofuels (Wang *et al*. 2011). In the production pathways of molasses-based ethanol, two additional products are manufactured which are sugar and electricity. The energy use and carbon emission has to be allocated among ethanol and the co-products that are produced along with it (Hammerschlag 2006, Wang *et al.* 2011, Nguyen and Hermansen 2012).

The mass-based method refers to the mass output shares as the basis to allocate energy use and emission burdens among multiple products. Since electricity, as a co-product of sugar and ethanol pathway, does not have a mass, the method would not allocate energy and emission to electricity generation. This is a major criticism of such method (Wang *et al*. 2011). The energy-content-based method uses the energy output shares as the apportionment rule. The energy output is calculated for all products by taking into account the energy content of the products. This method is suitable when the products are consumed according to their energy content such as a petroleum refinery system generating different types of petroleum products. The displacement method takes into consideration the products which are displace by non-fuels products to estimate the energy use and emissions burdens of producing the otherwise displaced products. The process-purpose based method estimates energy use and emissions of individual processes in a facility. This method is not appropriate when the processes lead to multiple products.

The market-value based method, advocated by economists, uses the economic value of individual products to allocate energy use and emission among co-products. Accordingly, price is the best available indicator of how much of a waste product such as molasses is worth (Gopal and Kammen 2009). If there is a surge in demand for molasses by ethanol producers looking to take advantage of the better lifecycle rating, the price of molasses will rise relative to sugar to a point where it can no longer be considered a waste or low value product. The other methods would not take the rise in prices into account unless the regulation is set based on the market value method. Gopal and Kammen (2009) argue that the strongest criticism of using market value is that it does not represent environmental outcomes. However, for this study, a distribution based on environmental outcome is difficult to apply and will result in grossly inaccurate results in this case as noted above.

Based on molasses based ethanol studies such as Nguyen et al. (2007), Nguyen *et al*. (2008) and Gopal and Kammen (2009) Khatiwada and Silveira (2011), the market-based method is used in this study. Further details are provided in sub-section 6.2.

5.5. Net Energy Balance and carbon emission

Equations (1) to (15) show the energy and carbon emitted during stage 1 that is feedstock preparation. Since the production of ethanol in Mauritius is a multiple products pathway, energy, carbon released and cost must be allocated to different products. Energy from 1 litre of ethanol is calculated as follows:

$$En_{ethanol} = E_{con} + AR_{mo}\left[\frac{E_{mo}}{80}\right] \tag{16}$$

$AR_{mo} =$ Apportionment Ratio to ethanol

$E_{mo} = E_f + E_\eta + E_{tf} + E_{t\eta} + E_x + E_m$

E_{con} = energy consumed in ethanol conversion

Since E_{mo} is the total energy used which is allocated to ethanol and the functional unit (one tonne of sugar), it means this level of energy is attributed to the equivalent of molasses and ethanol from one tone of sugar hence, the figure is divided by 80 to convert it into one litre of ethanol (given that one tonne of sugar gives 0.31 tonne of molasses and one tonne of molasses leads to 250 litres of ethanol).

Similarly, for carbon emission

$$CO2_{ethanol} = CO2_{con} + AR_{mo}\left[\frac{CO2_{mo}}{80}\right] \tag{17}$$

$CO2_{mo} = C_f + C_\eta + C_{tf} + C_{t\eta} + C_x + C_m$

$CO2_{mo}$ is the carbon emitted during the production segments up to and including sugar milling, (that is preparing of feedstock). The remaining parameters follow the above reasoning.

For the life-cycle cost (*LCC*), no equations are presented. However, it follows the same logic as above, that is:

$$LCC = COST_{con} + AR_{mo}\left[\frac{COST_{mo}}{80}\right] \quad (18)$$

$COST_{con}$ = cost involved in converting molasses into ethanol

$COST_{mo}$ =cost involved in the production of feedstock up to and including sugar milling.

6. Empirical results

The study provides a full chain analysis of energy and carbon emission with a life cycle cost assessment. The main segments for the assessment are energy and CO2 in the production of inputs for cane farming, transportation of inputs to cane fields, irrigating sugar cane field, transportation of sugar cane to factories, sugar milling and conversion of molasses as by-products into ethanol.

6.1. Defining the parameters used in the study

The parameters which are used during the energy and carbon assessment for ethanol are shown in table 1. A brief explanation is provided.

Table 1. Parameters for estimating net energy balance from ethanol production

Areas cultivated in hectares	62100 (ha)	
Areas harvested in hectares	58709 (ha)	All figures are for 2010
Tonnes of sugar cane cultivated	4366000	
Tonnes of sugar produced	452473	
1 hectare	74.4 tonnes of sugar cane	
1 tonne of sugar	9.64 tonnes of sugar cane	
1 tonne of molasses	250 litres of ethanol	
Functional unit	1 tonne of sugar, 1 tonne of sugar cane, 1 litre of ethanol	

Source: Digest of Agricultural Statistics, Digest of Energy statistics

Fertilisers and herbicides used in sugar cane cultivation:

The amount of fertiliser and herbicide which is used in the cultivation phase represents an important component which uses high energy and contributes to CO2. In Mauritius, the amount of Nitrogen, Phosphorous and Potassium (NPK) used in one hectare of sugar cultivation are 138kg, 50kg and 175kg respectively (Ramjawon 2008). Given the importance of inputs in energy and carbon assessment of ethanol bio-system, a comparison is made in table 2. Mauritius uses relatively more Nitrogen and Phosphorous than Thailand and Brazil but less than Nepal. Potassium is used significantly more than the other countries in the table 2. Section 7 of this study provides a simulation on changes in fertiliser and the associated impacts on energy and carbon indicators. The energy consumed in the production of fertiliser and herbicide per kg is 56.6MJ and 190MJ respectively (Ramjawon, 2004). The carbon emission factor is taken from the IPCC guidelines (IPCC 2007).

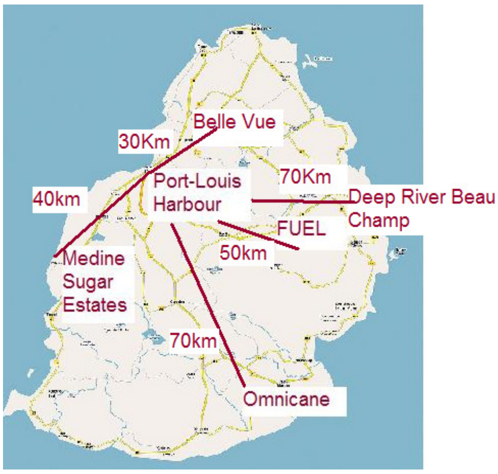
Table 2. Direct inputs use in cane cultivation

	Mauritius[a]	Thailand[b]	Nepal[c]	Brazil[d]
Fertilizers				
Nitrogen as N	138kg/ha	128kg/ha	140.03kg/ha	48kg/ha for plant cane, 75kg/ha and 88kg/ha for ratoon with and without stillage
Phosphorous as P_2O_5	50kg/ha	37kg/ha	50.95kg/ha	117kg/ha for plant cane and 114kg/ha for ratoon without stillage
Potassium as K_2O	175kg/ha	28kg/ha	55.4kg/ha	125kg/ha plant cane and 25kg/ha ratoon without stillage
herbicides	7.8kg/ha	10.6kg/ha	1.65kg/ha	2.2kgkg/ha
Irrigation	216kWh/ha	Na	295l of diesel /ha	
Source:	a Ramjaewon (2004, 2008)	b Nguyen et al (2008)	c Khatiwada and Silveira (2009)	d Macedo et al. (2008)

Energy used in irrigation: In Mauritius, on average 25% of land is irrigated and electricity is used in the process. It is assumed that electricity is generated from fuel oil. Data were obtained from the Digest of Agricultural Statistics (various issues) and from personal interviews with farmers in Mauritius.

Transportation: All materials, fuels and products (feedstock) involved in the system are hauled by transport systems with different characteristics. Data were collected through information exchange via personal interviews with officials from sugar factories, peer reviewed sources and educated assumptions and estimations. Figure 2 shows a graphical illustration of the transportation pathways in Mauritius which is used to estimate the average distance of transporting fertilisers, herbicides and sugar-cane to factory. The amount of diesel used per trip is 2.8litre with a load factor of 1500 per trip. The average distance for the transportation of fertilisers and herbicides from harbour to factory is 55km. The carbon emission factor from diesel is taken from IPCC guidelines.

Figure 2: Transportation of fertiliser and herbicides from harbour to factory



Source: authors

Sugar milling: Energy data associated with sugar milling were collected from sugar mills and from different sources such as Ramjawon (2004), (2008).

Ethanol combustion: Data for ethanol conversion was obtained from Environmental Impact Assessment Report of Omnicane Ethanol Production Ltd (EIA 2011). The company intends to install and operate a Distillery to produce ethanol using molasses. The Distillery will have the capacity to produce fuel grade (anhydrous) ethanol as well as potable hydrous. All relevant information as far as the conversion process is concerned, has been taken from the report. Personal interviews with officials of the company were also conducted to better understand the process and to cross-check the energy and carbon emission of the conversion pathway.

Data have been collected from different sources to calibrate the parameters in the study. Table 4 provides the system parameters, the definitions, and sources.

6.2. Apportionment rule based on economic value of multiple products

In this study, the market-based method is used to apportion energy consumption, carbon emission and cost estimates up to (and including) the phase of sugar milling among the different products which are derived from sugar cane as feedstock. One main product (sugar) and two by-products (electricity and molasses for ethanol) are identified. The average price of one tonne of sugar stands at Rs17105 in 2010. During the same period, 242.8GWh of electricity was exported to the Central Electricity Board (CSO 2011). This is equivalent to 78.5 KWh per tonne of sugar cane or equivalent of 536KWh per tonne of sugar. The purchase price of electricity by the Central Electricity Board is around 3.69 per KWh for 2009 (the 2010 figures are not available however, this figure is used since there is no much fluctuation between these two periods) (CEB 2010).

Again in the same period, the average price of one tonne of molasses was Rs3100. Since one tonne of sugar produces on average 0.31 tonne of molasses, the price has been adjusted accordingly to reflect the functional unit of this study which is one tonne of sugar. The apportionment rule which is derived from these figures is shown in table 4. Fluctuations in product market prices may affect the results.

Table 3: Economic apportionment rule between multiple products

	Sugar	Molasses	Electricity	Total
Apportionment Rule %	85.2	5.0	9.8	100

Source: calculated

Table 4: Production system parameters

Parameter	Definition	Source
h	Amount of hectare used for sugar cane cultivation	Digest of Agricultural Statistics, CSO, Mauritius
f	Fertiliser (NPK) in kg used per hectare	Ramjawon (2004)
f_k	Heat (energy) consumed (LHV) in production of fertiliser per kg in (MJ)	Ramjawon (2004)
s	Tonne of sugar produced	Digest of Agricultural Statistics
y_s	Sugar yield per hectare	Digest of Agriculture Statistics
f_c	Carbon emission factor per kg of fertiliser	IPCC guidelines
η	Amount of herbicide used her hectare (kg)	Ramjawon (2004), Ramjawon (2008)
η_k	Energy used to produce 1 kg of herbicides (in MJ)	Ramjawon (2004), Ramjawon (2008)
η_c	Carbon emission factor in the production of herbicide (kg/kg)	IPCC guidelines
d	Amount of diesel consumed per trip (in litre)	Survey and interviews
d_e	Heat (energy) content of diesel (MJ)	Survey and interviews
l_f	Average distance for transportation of fertiliser	Survey and interviews
l_η	Average distance for transportation of herbicide	Survey and interviews
$load_f$	Carrying capacity of a truck for fertiliser and herbicide (in tonne)	Survey and interviews
d_c	Carbon emission factor for one litre of diesel (g)	IPCC guidelines
l_s	Average distance for transportation of sugar cane	Interview and authors calculation

$load_s$	Carrying capacity of a truck for sugar cane transportation	Survey
x	Amount of electricity consumed per hectare for irrigation (KWh)	Ramjawon (2004)
x_p	Percentage of land irrigated	Digest of Agriculture Statistics
x_e	Heat (energy) content for electricity (MJ)	IPCC guidelines
x_c	Carbon emission factor for electricity generation (fuel oil) (g)	IPCC guidelines
x_m	Electricity used per tonne of sugar cane	Ramjawon (2004)

6.3. Result 1: Energy Assessment

Table 5 shows the energy consumed in each segments of the system boundary. Bagasse is a by-product of sugar cane crushing and sugar manufacturing, which is used to manufacture electricity. Since bagasse is derived from biomass which is sugar cane, the carbon released is eventually absorbed through photosynthesis in sugar cane (Prakash *et al*. 1998). This segment is assumed to be a renewable energy segment.

Table 5. Energy assessment

Functional unit= 1 tonne of sugar	MJ
Energy in the production of fertiliser (NPK)	2819.82
Energy in the production of herbicide	203.40
Energy used in transportation of fertiliser	18.93
Energy used in the transportation of herbicide	0.41
Energy used in irrigation	26.68
Energy used transportation of sugar cane to factory	576.72
Energy used in the manufacturing phase	788.41
Total energy used (fossil + renewable energy)	**4434.36**
Energy credit	788.41
Total energy used (fossil fuel)	**3645.96**

Source: authors

Based on the economic apportionment rule, 5.0% is attributed to ethanol, that is, 221.72MJ of total energy (fossil and renewable) and 182.30 MJ of fossil fuel used. For 1 tonne of sugar, 80litres of ethanol is obtained. This amounts to 2.77MJ of total energy used (fossil and renewable) and 2.28 MJ of fossil fuel per litre of ethanol.

The ethanol conversion technology uses 2.09 MJ per litre of ethanol. In this respect, the following indicator is calculated:

Net Energy Balance (NEB) = 21.2 – 4.86 = 16.34 MJ per litre of ethanol

Net Renewable Energy Balance (NRnEB) = Energy content in ethanol – fossil fuel consumed = 21.2 – 2.28 = 18.92 MJ per litre of ethanol

Energy yield (ER) = 21.2/2.11=9.30 MJ per litre of ethanol.

6.4. Result 2: carbon emission assessment

The carbon emission assessment follows the same reasoning as in section 6.3. Table 6 provides the results. Since the energy for ethanol conversion is obtained from steam, there is no carbon emission in the conversion phase.

Table 6. Carbon emission assessment for ethanol production pathway

Functional unit= 1 tonne of sugar	Gram (g)
CO2 in the production of fertiliser (NPK)	19928.08
CO2 in the production of herbicide	1605.78
CO2 in transportation of fertiliser	1360.00
CO2 in the transportation of herbicide	290.00
CO2 in irrigation	41593.22
CO2 in transportation of sugar cane to factory	2060.33
Total carbon emission	**66581.60**
No carbon emission for ethanol conversion	

Source: authors

The calculation leads to an estimate of 41.91g of CO2 per one litre of ethanol. Given that ethanol is expected to replace gasoline, 1 litre of gasoline emits 2321.7g of CO2. Replacing 1 litre of gasoline by 1 litre of ethanol derives less heat however. Hence, 1 litre of ethanol is expected to replace 1509.2 g of CO2. The net carbon emission avoided in estimated at (1509.2-41.91) = 1467.29 g of CO2 or 1.47 t of CO2 per litre of ethanol. Carbon emitted during combustion of biofuels was not taken into account, as it is assumed that this carbon had been captured as CO2 from the atmosphere by photosynthesis during plant growth (Graefe *et al*. 2011).

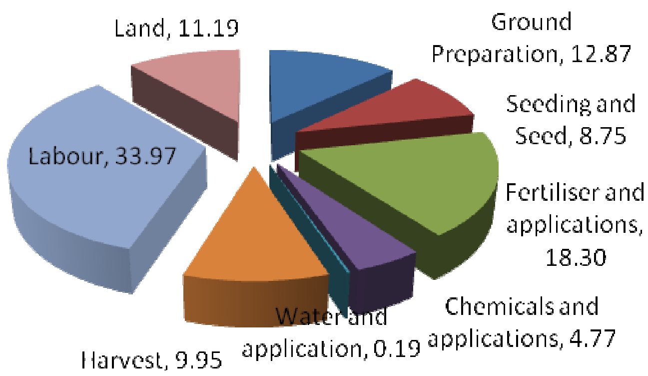
6.5. Result 3: Life-cycle cost assessment

The life-cycle cost of producing ethanol using molasses from sugarcane as feedstock is worked out from Professor William Jaeger work book (2008). The sugar cane farming costs are depicted in table 7.

Table 7. Feedstock Production Costs		
Feedstock Production	Units	Costs in 2010
Ground Preparation	Rs/hectare	11,494.5
Seeding and Seed	Rs/hectare	7,821
Fertiliser and Applications	Rs/hectare	16,353
Chemicals and Applications	Rs/hectare	4,266
Water and Applications	Rs/hectare	169
Harvest	Rs/hectare	8,887.5
Labour	Rs/hectare	71,929.5
Land	Rs/hectare	10,000
Total	Rs/hectare	**130,920.5**
Source : authors (different sources)		

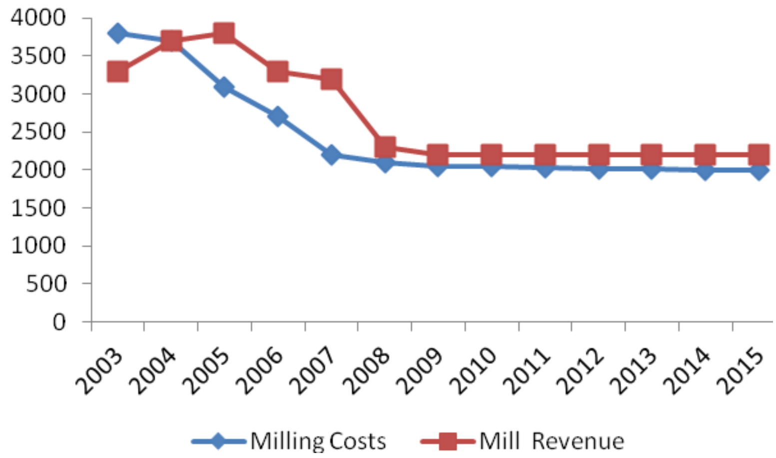
Labour costs represent the highest cost component with around 34 percent of total production costs followed by fertiliser with 18.30 percent and ground preparation with 12.87 percent. This is shown by Figure 3 below.

Figure 3: Distribution of Production Costs in 2010



The milling costs for 2010 turn out to be around Rs 2,050 per tonne (figure 4)

Figure 4: Milling cost



Source: MAAS (2005)

The total production and milling costs of sugar cane are shown in the following:

Table 8: Total Production and Milling Costs in 2010

Costs	Calculation	Rs/tonne
Total Sugar Production Costs per hectare	130,920.5	
Sugar Yield (tonne/hectare)	7.7	
Sugar Production costs per tonne	=(130,920.5/7.7)	17098.9
Sugar Milling costs per tonne		2,050.0
Total Production and Milling Costs		**19,148.9**

Source : *Authors (calculated from data from different sources)*

Ethanol conversion cost

The production cost, inclusive of financial costs and return on capital, of one litre of ethanol from cane biomass substrates is around Rs6.00 /litre. The transport cost to the blending station is around Rs 2.00. Given a price of molasses of Rs12, the ethanol LCC is around Rs20, with feedstocks amounting to 60%.

7. Sensitivity analysis and discussion

7.1. Summary of findings and discussion

For molasses-based ethanol, diverging yield ratios are found in the literature. For India and South Africa, the energy yield ratio is 48 and 1.1 respectively, implying that the system returns an energy output of 48 and 1.1 times the energy input (Blottnitz and Curran 2007). In the previous case, the two diverging results for molasses relate to the fact that in the Indian case, the distillery is fully integrated into a sugar mill, where excess low pressure steam is used; whereas in the South African case, the distillery is distant from sugar mills, relying on coal and grid electricity for its energy needs. Khatiwada and Silveira (2009) in turn show that the energy yield ratio for Nepal 7.47 with an NRenB of 18.36. Prakash *et al*. (1998) estimate a NRenB of 11.37MJ/L for India. For Thailand, the NRenV is 5.95MJ/L (Nguyen et al. 2008)

In Mauritius the distillery plant is integrated in the sugar mill and steam is used and hence, a figure of 9.24 MJ per litre is obtained. Table 9 provides a summary of findings per litre of ethanol and per hectare.

Table 9: Summary of findings: energy balance, carbon avoided and life-cycle cost assessment

	Per Litre	Per hectare
Fossil fuel consume up to and including sugar milling (MJ)	2.30	1129.12
Net renewable energy value (NRnEV) (MJ)	18.91	9301.29
Energy yield ratio	9.24	9.24
Carbon emission avoided (kg)	1.47	721.91
Cost per MJ (Rs per MJ)	1.10	541.39
Cost per CO2 avoided (Rs/g)	12.64	6217.56

Source: calculated

Energy input is the manufacturing of fertiliser and herbicide has the largest share. Similar conclusion is drawn in Nguyen et al. (2008). In this study, it represents 63.6% of the life-cycle energy assessment (table 10).

However, in terms of carbon emission, the transportation of sugar cane to factory represents the largest share as 62.2% of CO2 is emitted during the transportation phase. It is important to note that bagasse is used in the sugar milling. This energy represents 17.8% and therefore it is subtracted in the energy yield ratio.

Table 10. Percentage distribution of energy in ethanol pathway

Functional unit= 1 tonne of sugar	% distribution of energy consumed	% distribution of carbon emission
The production of fertiliser (NPK)	63.59	29.82
The production of herbicide	4.59	2.40
Transportation of fertiliser	0.43	2.03
The transportation of herbicide	0.01	0.43
Irrigation	0.60	3.08
Transportation of sugar cane to factory	.13.01	62.23
Total	**100**	**100**
Energy credit	17.78	

Source: authors

7.2. Cost and benefit analysis of ethanol production – accounting for the external cost of CO_2

Cost effectiveness based on private cost accounting

An important contribution of this study is an analysis of the cost-effectiveness of producing bio-ethanol as a way to reduce CO_2. The cost involved in producing the fuel and the consumption and importation of conventional gasoline is important in this respect. The amount of imported gasoline stands at 153.7m litres for 2010 and the CIF value is Rs3417.8m (around $US112m). This figures show that one litre of gasoline costs Rs 22.2 ($US0.72).

The life-cycle cost of ethanol production up to conversion of molasses to ethanol is around Rs20 given an estimated cost of feedstock from the study (Rs12), representing an operating cost of 40%. However, the energy content of ethanol is less than that of gasoline. From the estimates of this study, the energy content for 1 litre of ethanol is 18.92MJ. Hence, for 1 MJ of ethanol, it costs the economy Rs1.06. Alternatively, feedstock (molasses) can be sold to its other uses and the investment cost associated with the conversion process of ethanol may be diverted towards other productive sectors.

Conventional gasoline has a higher heat content, 32.4 MJ and the cost which is incurred for 1 MJ is Rs0.68. Compared to the cost of producing ethanol, the option of importing gasoline is more cost effective. The economic analysis of ethanol implies that it may be more viable to export molasses and divert the resources such as land, labour and capital used for ethanol conversion to more efficient productive sector (the opportunity cost principle). In countries where gasoline is being manufactured, the life-cycle cost of gasoline production would be the relevant indicator.

Based on the above calculation, it is more cost effective to import gasoline than to produce ethanol, even if ethanol has a net positive energy balance. To be cost effective compared to gasoline, the cost of producing one litre of ethanol should be Rs12.87 – this is unlikely since the cost of feedstock itself is Rs12.

It is also worth mentioning that the Brazilian experience in this area led to ethanol produced at very low cost and competitive with gasoline through gains in productivity and economies of scale (Goldemberg, 2007). Coehlo et al. (2006) show that the ethanol production cost was higher than the price of gasoline up to the late 1990s in Brazil. The cost fell steadily since the 1980s and the gap between the cost and gasoline prices reduced drastically after 1999. The learning process in terms operating the biofuel systems and managing feedstock plays a key role in this respect.

Cost effectiveness based on social cost accounting

The IPCC (2007) defines the social cost of carbon as the value of the climate change impacts from 1 tonne of carbon emitted today as CO_2, aggregated over time and discounted back to the present day. According to economic theory, the intersection of the marginal abatement cost and a curve for marginal benefit shows that is worth reducing CO_2 emission up to the point where the marginal benefits equal marginal cost. Hu *et al*. (2004) argue that the external cost of CO_2 refers to the ecology costs of global warming caused by the CO2 investment that is the monetary value of worldwide damage done by anthropogenic CO2 emissions. Duong (2009) reports that the social cost is influenced by a number of factors including the deep-seated scientific uncertainty (abrupt climatic changes), double dividends and other factors such as discounting, risk aversion and equity issues. Duong (2009) points out that the 200 Euro per tonne of CO2 threshold can be viewed as the limit to the unknown parameters while the minimum threshold is around 5 Euro per tonne of CO2.

Taking the minimum of 5 Euro per tonne of CO2, 1 tonne of CO2 will cost the society Rs41.9 (2010 figures). Since 1 litre of gasoline emits 2.32 t of CO2, the external cost of 1 litre of gasoline is Rs486.04.

Social cost = private cost + external cost = 22.2+486.04=Rs486.04.

Thus, 1 MJ of gasoline has a cost of Rs15.09. Compared to ethanol with a cost of Rs 1.06 per MJ, ethanol eventually become a viable environmental option and is a cost-effective to reduce carbon emission.

The economic analysis shows that other external cost may be added to the LCC of biofuel to have a complete examination of its economic and environmental feasibility. Since molasses-based ethanol does not reduce forest land or lead to increases in prices of food crops in Mauritius, no external cost is added to the LCC of ethanol production. However, sugar-cane based molasses may lead to external cost if GHGs rises with land use changes.

7.3. Sensitivity analysis of a reduction in the consumption of fertiliser

As Blottnitz and Curran (2007) point out, the physical differences are the main factors leading to differing energy and carbon assessment. Table 11 shows the effects of reducing fertilisers by 20% in Mauritius. As shown in table 2, page 16, fertilisers vary substantially given the geography.

Table 11. Reduction in fertiliser

	Per hectare (initial estimate) (MJ)	20 % reduction in NPK (MJ)	Effects
Fossil fuel consume for ethanol up to and including sugar milling	1129.12	962.98	15 % reduction
Net renewable energy value (NRnEV) (MJ)	9301.29	9467.42	1.71% increase
Energy yield ratio	9.24	10.83	13.68% increase
Carbon emission avoided (kg)	721.91	723.15	0.17% increase
Cost per MJ (Rs per MJ)	0.981	0.964	Na
Cost per CO2 avoided (Rs/g)	12.637		Na

Source: calculated

The assessment shows that a fall in NPK by 20% reducing the energy consumed on the ethanol pathways by 15% and increases the net renewable energy balance by 1.71%. The energy yield ratio also increases by 13.7%.

7.4. Changes in distance of sugar cane transportation

Transportation of feedstock to factory is another segment which consumes substantial energy. In the present case, the average distance travelled is 15km. This is the result of the centralisation policy which Mauritius has adopted to reduce cost of production. Table 12 provides the results of a sensitivity analysis if the average distance is 7km that is a reduction of 50%. This figure was indeed the distance travelled a decade ago before the closure of some sugar factories throughout the island (Ramjawon 2004).

Table 12. Changes in transportation of feedstock

	Per hectare (initial estimate)	7km average distance of sugar cane transportation	
Fossil fuel consume for ethanol up to and including sugar milling	1129.12	1033.86	8.4 % reduction
Net renewable energy value (NRnEV) (MJ)	9301.29	9396.54	1.03% increase
Energy yield ratio	9.24	10.09	9% increase
Carbon emission avoided (kg)	721.91	728.78	0.95% increase

Source: calculated

As can be seen, the change in fossil fuel is around 8.4%.

7.5. Fossil fuel electricity for sugar milling

Sugar milling uses bagasse as an input to manufacture electricity. The following table shows the effect if electricity was generated using fuel oil. The effect shows that the non-renewable energy would increase by 21.6% while the energy balance would decrease by 2.63%. The energy yield ratio is affected – 17.8% reduction- from 9.24 to 7.59 and finally carbon emission avoided reduces by 9.4%.

Table 13. Fossil fuel for sugar milling

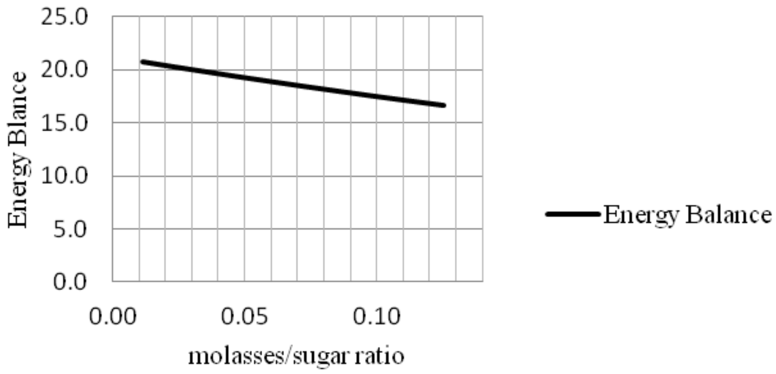
	Per hectare (initial estimate)	Fossil fuel for sugar milling	
Fossil fuel consume for ethanol up to and including sugar milling	1129.12	1373.27	21.6 % increase
Net renewable energy value (NRnEV) (MJ)	9301.29	9057.13	2.63% decrease
Energy yield ratio	9.24	7.59	17.8% decrease
Carbon emission avoided (kg)	721.91	654.03	9.40% decrease

Source: calculated

7.6. Sensitivity analysis of changes in the economic value of co-products

As mentioned above, the apportionment rule is based on the economic value of the co-products. The ratio of the economic value of molasses to sugar stands at 0.06 in 2010 or 1:17. In this section, a sensitivity analysis is conducted by varying the ratio from 0.01 to 0.1. A higher ratio of molasses shifts the energy, emission and cost involved in the production pathway to molasses and eventually to ethanol. This means that as the economic value of molasses goes up, more energy and emission as well as the life-cycle cost are attributed to ethanol. Such scenarios change all the indicators. Figure 5 shows the impact on energy balance when the molasses/sugar ratio in terms of their economic value changes from 0.01 to 0.1.

Figure 5. Sensitivity analysis Molasses/Sugar ratio on Energy Balance of ethanol

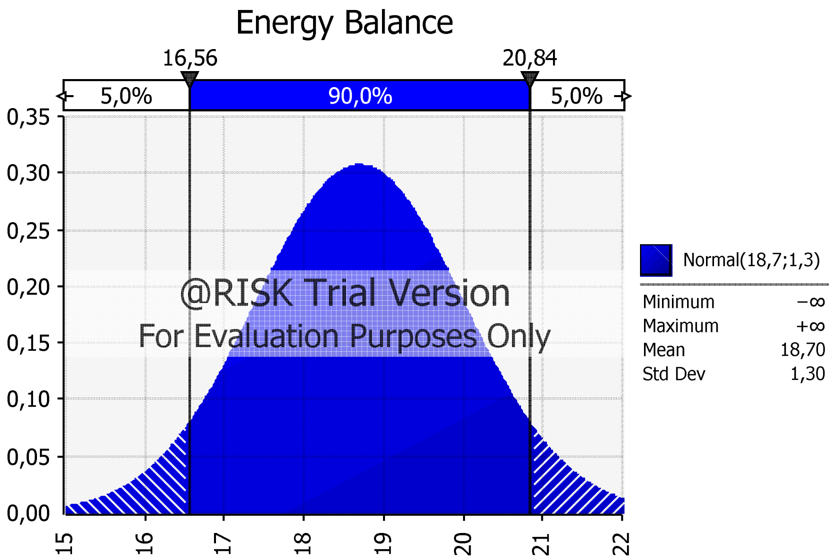


Source: estimated

As shown in the diagram below, net renewable energy balance falls from 20.7 when the ratio is 0.01 to 16.6 when the ratio rises to 0.1.

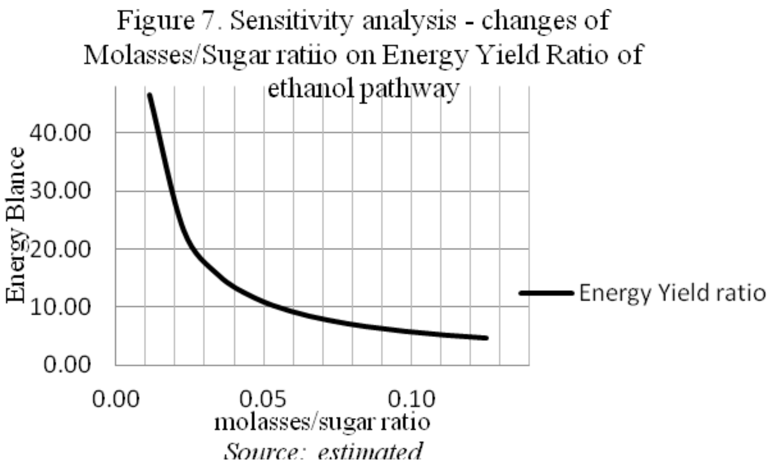
By varying the apportionment ratio, a set of variables for energy balance is created and based on the parameters (mean and standard deviation), the range of estimates which may be expected with changes in the apportionment ratio is simulated using the *@Risk* decision tool software. A normal distribution is used to approximate the distribution. As shown in Figure 6, the range 16.56-20.84 forms the 90% area under the Normal distribution curve.

Figure 6: Simulation of energy balance with changes in molasses/sugar ratio



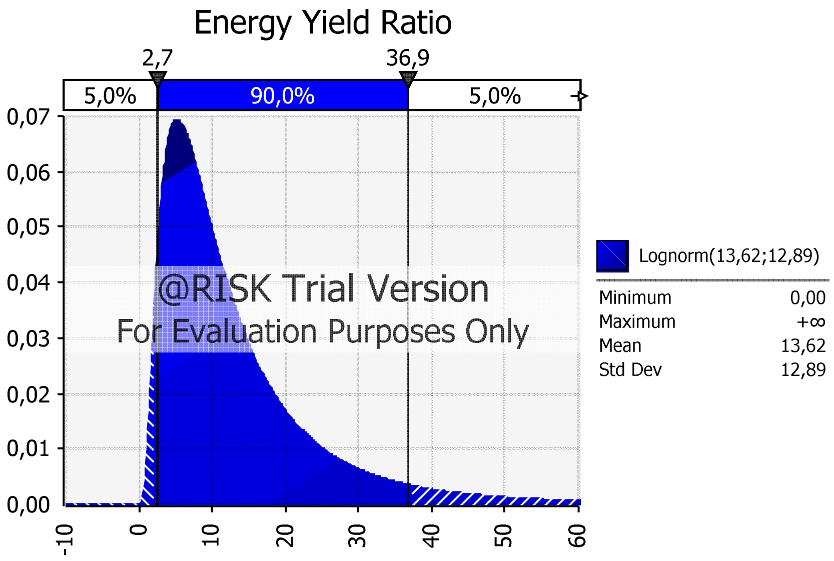
Source: @*Risk* (trial version)

The next exercise is to analyse the range of estimate for the energy yield following changes in the ratio. Figure 7 shows the findings.



The change is substantial in terms of the energy yield ratio. It moves from 46 when the ratio is at its minimum and decline to 5 as the ratio goes up to 0.1. The estimated ratio in 2010 is 0.06 and hence, the yield ratio stands at around 9. The @Risk simulation exercise shows that the energy yield ratio falls between the range of 2.7- 36.9 within the 90% interval of the lognormal distribution.

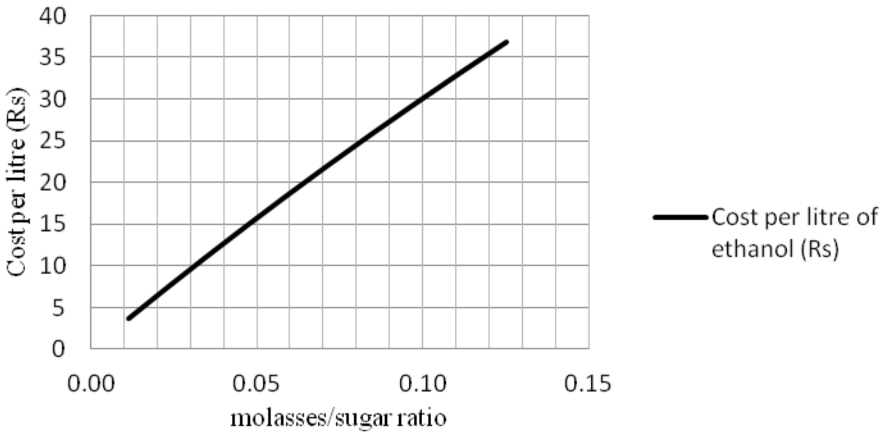
Figure 8: Simulation of energy yield ratio with changes in molasses/sugar ratio



Source: @Risk (Trial version)

Given the assumption in this study, the rise in cost is proportional to the increase in the molasses/sugar ratio. A possible avenue of research is to investigate the non-linear relationship between life-cycle cost of ethanol pathway.

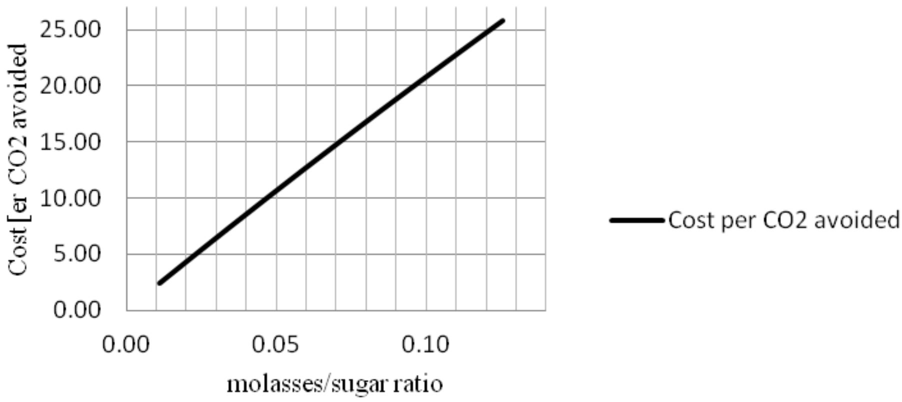
Figure 9 Sensitivity analysis - Molasses/Sugar ratio on cost of ethanol pathway



Source: estimated

Similarly, the cost per CO2 avoided changes with variation in the ratio.

Figure 10. Sensitivity analysis Molasses/Sugar ratiio on cost per CO2 avoided



Source: estimated

7.7. Comparison: tax versus ethanol production

It is also worth to analyse in tax equivalent which may induce the effect of reducing carbon emission by decreasing gasoline consumption through a higher tax. Based on the gasoline demand equation (Sultan 2010), $log\,G = -0.896 - 0.441LogP + 0.773LogY$, the price elasticity of demand is 0.44. Since 145000tonne of molasses is produced, produced an amount of 36.2m litres of ethanol, the equivalent reduction in gasoline is 23.5m litres. Given the imports of gasoline for 2010 stands at 153.7m litres, this represents a fall in gasoline consumption of 15%. According to the demand equation, the rise in price should be 34%, which would mean a rise in price by Rs16.6.

7.8. Limitations of the empirical results

It is important to emphasise that the indicators of energy balance and carbon emission avoided in this study are calculated using parameters which are not based on an economic optimisation model. In particular, the approach assumes the selection of particular production processes which may or may not be the best choices. The production relationships are not based on actual production functions and are not showing the input and output relationship with an optimising behaviour. A number of arbitrary assumptions are made in relation to production processes such as feedstock preparation (sugar cane cultivation and harvest), sugar milling and ethanol conversion. These assumptions reflect production at one point in time and in some cases, they are based on international practices.

It is acknowledged that the present analysis is necessary in the absence of information and is a useful building block in the construction of models incorporating economic decision-making. It may pave the way for future work on this subject. Future avenues include integrating the optimising behaviour of economic agents and estimates from production functions in the calculation, the assessment of economies of scale and scope of ethanol production system, and the non-linear relationship between net energy gain, carbon emission avoided and LCC.

8. Conclusion

Energy balance and carbon emission avoided are increasingly used to assess ethanol production pathways. Recently, life-cycle cost assessment of biofuel systems has been integrated in the analysis to assess the cost-effectiveness of ethanol development. By using the LCC, together with energy balance and carbon emission, from an economic perspective, further insights on which options can best attain the objectives of energy security and reducing fossil fuel and CO2 can be obtained.

This study adds to the literature on molasses-based ethanol production. It is the first study conducted in Mauritius. The renewable and non-renewable energy consumed during the different production processes is calculated, together with its associated CO2 and the life-cycle cost involved. The findings indicate that net renewable energy balance stands at 18.92MJ with an energy yield of 9.30MJ per litre of ethanol. Given the life-cycle cost assessment, it costs the economy Rs1.06 to produce 1 MJ of ethanol given its energy content is lower than gasoline. Therefore, ethanol production is not cost-effective when compared to the cost incurred for gasoline (which stands at Rs0.68 per MJ). However, the carbon emission avoided is high with the consumption of ethanol, given that ethanol is a renewable resource. When the external cost of carbon emission is added to the (private) cost of gasoline, ethanol becomes socially feasible.

Energy balance for ethanol production system varies substantially worldwide, in relation to factors such as geographical location, characteristic of feedstock, and conversion technologies, among others. A sensitivity analysis is undertaken to analyse the extent to which the energy and carbon indicators are influenced by production inputs and technologies. Amount of fertiliser consumed, transportation of sugar cane to factory, fossil fuel used in electricity generation and ethanol conversion method are all essential factors which influence energy and carbon indicators (energy yield and carbon emission avoided).

The specificity of the Mauritius ethanol production system is that there are multiple products besides molasses. Hence, a method is used to distribute the energy used and CO2 associated with production segments up to the sugar milling. The rule is based on the economic value of the products. Eventually, the price ratio between molasses and sugar plays an important role in the estimates. A simulation exercise is undertaken to examine the variation of energy balance and energy yield with respect to changes in the economic value of molasses. The simulation exercise shows that there is significant variation in energy balance (16.59-20.84) and energy yield (2.7-36.9) which may be attributed to the apportionment method. These factors may explain the wide differences in such indicators worldwide.

The study has focused only on CO2 as greenhouse gases. A full life-cycle assessment is not within the scope of this study. However, following the economic analysis in terms of social cost, net energy gain, net carbon emission avoided, a full LCA may provide more insights on biofuel pathways. Moreover, there may be non-linear relationship between net energy gain, carbon emission avoided and LCC. These lines provide future avenues of research in this field.

References

Amigun B, Sigamoney R, von Blottnitz H. 2008. Commercialisation of biofuel industry in Africa: a review. Renewal Sustainable Energy Review 12, 690-711.

Balat, M., Balat, H., 2009. Recent trends in global production and utilization of bioethanol fuel. Applied Energy 86, 2273–82.

Blottnitz, H., Curran, M. A., 2007. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life-cycle perspective. Journal of Cleaner Production, 15, 607-619.

Botha, T., von Blottniz, H., 2006. A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis. Energy Policy 34 (17), 2654–2661.

Borrero, M., Pereira, J. T. V. Miranda, E. E., 2003. An environmental management method for sugar cane alcohol production in Brazil, in: Biomass and Bioenergy, 25, 287 – 299.

Coelho, S. T., Goldemberg, J., Lucon, O., Guardabassi, P. 2006. Brazilian sugarcane ethanol: lessons learned. Energy for Sustainable Development, Vol. X. No. 2.

Cortez, L.A.B., Griffin, M.W., Scaramuchi, J.A., Scandiffio, M.I.G., Braunbeck, O.A., 2003. Considerations on the world use of bioethanol as contribution for sustainability. Management of Environmental Quality 14 (4), 508–519.

CSO. 2011. Digest of Energy Statistics, Central Statistics Office, Mauritius.

Demirbas, A. (2001) Biomass Resource Facilities and Biomass Conversion Processing for Fuels and Chemicals, Energy Conversion and Management 42 (11), 1357-1378.

Demirbas, A. 2006a. Energy priorities and new energy strategies. Energy Edu. Sci. Technol. 16, 53–109.

Demirbas, A. 2006b. Sustainable Biomass Production. Energy Sources, Part A 28, 955–964.

Duong, M. H. 2009. What is the Price of Carbon? Five definitions. S.A.P.I.A.N.S. 2, 1, 1-5.

EIA. 2011. Installation and operation of a Distillery and a CMS Fertiliser Blending Plant at La Baraque. Environmental Impact Assessment Report, Ministry of Environment, Mauritius.

Fu, G. Z., Chan, A. W., Minns, D. 2003. Life cycle Assessment of Bio-ethanol derived from Cellulose. International Journal of Life cycle Assessment, 8 (3) 137-141.

García C.A, Fuentes A, Hennecke A, Riegelhaupt E, Manzini F, Masera O. 2011. Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico. Applied Energy 88, 2088–2097

Giampietro, M., Ulgiati, S., 1997. Feasibility of large-scale biofuel production. Bioscience 47 (9), 587–601.

Goldemberg, J., 2007. Ethanol for a Sustainable Energy Future. Science 315, 808-810

Goldemberg, J., Coelho, S. T., Guardabassi, P. 2008. The sustainability if ethanol production from sugarcane. Energy Policy 36, 2086-2097.

Gopal A. R , Kammen D. M, 2009. Molasses for ethanol: the economic and environmental impacts of a new pathway for the lifecycle greenhouse gas analysis of sugarcane ethanol, Environmental Research Letters , 044005

Graefe, S., Dufour, D., Giraldo, A., Munoz, L. A., Mora P., Solis H., Garcés H., Gonzalez A.. 2011. Energy and carbon footprints of ethanol production using banana and cooking banana discard: A case study from Costa Rica and Ecuador. Biomass and bioenergy 35 (7), 2640-2649.

Hammerschlag, R., 2006. Ethanol's Energy Return on Investment: A Survey of the Literature 1990-Present. Environmental Science and Technology, 40, 1744-1750.

Henke, J.M., Klepper, G., Schmitz, N., 2005. Tax exemption for biofuels in Germany: is bio-ethanol really an option for climate policy? Energy 30, 2617–2635.

Hu, Z., Fang, F., Ben, D., Pu, G., Wang., C. 2004. Net Energy, CO2 emission, and life-cycle cost assessment of cassava-based ethanol as an alternative automotive fuel in China. Applied Energy 78, 247-256.

IEA (International Energy Agency). 2004. Biofuels For Transport: A International Perspective. 9 rue de la Fédération, 75739 Paris, cedex 15, France. (available from: www.iea.org).

IPCC 2007. Glossary. http://www.ipcc.ch/pdf/glossary/ar4wg2.pdf.

Khatiwada, D., Silveira, S. 2009. Net energy balance of molasses based ethanol: The case of Nepal. Renewable and Sustainable Energy Reviews 13, 2515-2524.

Kheshgi, H., Prince, R., and Marland, G. 2000. The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. Annual Review of Energy and the Environment, 25(1), 199-244.

Kheshgi HS and Prince RC, 2005. Photobiological production of hydrogen: potential efficiency and effectiveness as a renewable fuel. Crit Rev Microbiol, 31, 19-31.

Larson ED 2005. Liquid Biofuel Systems for the Transport Sector. GEF/STAP Workshop on Liquid Biofuels. Aug 29-Sept 1. New Delhi, India. (www.unep.org/stapgef/ documents/ Wshop_docs/liquid_biofuels_2005/Back%20Ground%20Papers /BackGround%20Paper%201St.pdf).

Leite R, Leal M, Cortez L, Griffin W.M, Scandiffio M. 2009. Can Brazil replace 5% of the 2025 gasoline world demand with ethanol? Energy 34, 655–661)

Levelton, R., 2000. Assessment of net emissions of greenhouse gases from ethanol-gasoline blends in Southern Ontario, Cross-Sectoral Policy Development Division.

Macedo, I. C. 1998. Greenhouse gas emissons and energy balances in bio-ethanol production and use in Brazil (1996), Biomass and Bioenergy 14 (1), 77-81.

Macedo, I.C., Seabra, J.E.A, Silva, J.E.A.R. 2008. Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy.

Mollersten K, Yan J, Moreira JR 2003. Potential market niches for biomass energy with CO2 capture and storage—opportunities for energy supply with negative CO2 emissions. Biomass Bioenergy 25(3), 273–285

Moreira, J.R. and J. Goldemburg. 1999. The Alcohol Program. Energy Policy. 27 (229).

Nguyen, T. L. T., 2008. Full chain energy analysis of fuel ethanol from cane molasses in Thailand. Applied Energy, 85, 722-734.

Nguyen, T. L. T., Hermansen, J. E. 2012. System expansion for handling co-products in LCS of sugar cane bio-energy systemsL GHG consequences of using molasses for ethanol production. Applied Energy 89, 254-261.

Nguyen T. L. T., Gheewala, S. H., and Garivait, S., 2007. Fossil energy savings and GHGs mitigation potentials of ethanol as a gasoline substitute in Thailand. Energy Policy, 35, 5195-5205.

Nguyen T. L. T., Shabbir H. Gheewala, S. G. 2008. Full chain energy analysis of fuel ethanol from cane molasses in Thailand, Applied Energy 85, 722–734

Niven, R.K. 2005. *Ethanol in gasoline: environmental impacts and sustainability review article*. Renewable and Sustainable Energy Reviews 9, 535–555.

Oliveira, M. E. D., B. E. Vaughan, and E. J. J. Rykiel, Jr. 2005. Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. Bioscience 55:593–602.

Pimental, D., 2001. The Limits of Biomass Energy, Encyclopedia of Physical Science and Technology, vol. 2, third ed. Academic Press, New York, pp. 1–12.

Restianti, Y. Y., Gheewala, S. H. 2012. Environmental and Life Cycle Cost Assessment of Cassava Ethanol in Indonesia. Journal of Sustainable Energy and Enviroment 3, 1-6.

Prakash, R., Henham, A., Bhat, I. K. 1998. Net energy and gross pollution fro bioethanol production in India. Fuel 77(14) 1629-1633.

Ramjeawon T. 2004. Life cycle assessment of cane-sugar on the Island of Mauritius. International Journal Life Cycle Assessment 9 (4), 254–60.

Ramjeawon T 2008. Life cycle assessment of electricity generation from bagasse in Mauritius. Journal of Cleaner Production 16, 1727-1734

Restianti, Y.Y., Gheewala, S.H. 2012. Environmental and life cycle cost assessment of cassava ethanol in Indonesia, Journal of Sustainable Energy and Environment, 3 (1), 1-6.

Rojid S., Tandrayen V., Seetanah B and Sannassee V. 2009. Trade and Poverty in Mauritius:Impact of EU Sugar Reforms on the Livelihood of Sugar Cane Workers. Trade and Industrial Policy Strategies Paper. http://www.tips.org.za/files/Sawkut-final-_15_12.pdf

Schlamadinger B, Apps M, Bohlin F, Gustavsson L, Jungmeier G, Marland G, et al. 1997. Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass Bioenergy,13(6), 359–75

Shapouri, H., Duffield, J.A., McAloon, A., Wang, M., 2004. The 2001 Net Energy Balance of Corn Ethanol. US Department of Agriculture.

Sims, R.E.H. 2004. Biomass, Bioenergy and Biomaterials - future prospects, ‘Biomass and Agriculture - sustainability markets and policies’. p. 37-61. OECD, Paris.

Sims, R. E. H., Mabee, W., Saddler, J. N., and Taylor, M. 2010. An overview of second generation biofuel technologies. Bioresource Technology 101, 1570-1580.

Silalertruksa Thapat, Shabbir H. Gheewala 2009. Environmental sustainability assessment of bio-ethanol production in Thailand, Energy 34, 1933–1946.

Sultan. R. 2010. Short-run and long-run elasticities of gasoline demand in Mauritius: an ARDL bounds test approach. Journal of Emerging Trends in Economics and Management. 1(2), 90-95

Wang, M., Huo, H., and Arora, S.., 2011. Methods of dealing with co-products of Biofuels in life-cycle analysis and consequent results within the U. S. context. Energy Policy, 39, 5726-5736.

Zafar, A. 2011. Mauritius: An Economic Success Story. In *Yes Africa Can Success stories from a dynamic continent*. Edited by P. Chuhan-Pole and M. Angwafo. The International Bank for Reconstruction and Development / The World Bank.

Zhang, C., Han, W., Jing, X., Pu, G., Wang, C. 2003. Life cycle economic analysis of fuel ethanol derived from cassava in southwest China. Renewable and Sustainable Energy Reviews 7, 353-366.