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Energetics and Water Requirement of a Commercial-Scale Sweet Sorghum Ethanol Production

ABSTRACT

This study quantifies the energy balance and water requirement for ethanol production from sweet sorghum. The energy balance assessment is important to verify if the system actually achieves a positive net energy balance, while inventory of water requirement provides primary approximation of the water economy of this alternative feedstock. The boundary of the assessment is from the production of the feedstock to the products' end-use (cradle-to-grave). All the balances were based from a 30-M L yr^{-1} capacity commercial bioethanol plant that operates for 270 d yr^{-1}. The net energy balance of the system was computed by accounting the total energy consumed by the materials and processes in the boundary equated with the total energy produced through the products – power and biofuel. From the assessment, it was verified that the production gains a net energy equivalent to 475,621,789.51MJ yr^{-1} or 15.85 MJ L^{-1} of ethanol produced. Since the assessment assumed that a new bioethanol facility will be put up, the analysis included the energy invested during this pre-operational period, termed as "energy debt." Construction of the whole facility expended a total of 1,127,076,244.75MJ energy or 37.57 MJ L^{-1} ethanol. However, because the system gains a net energy, a payback period for the energy invested was computed by dividing the total energy debt by the net energy gain. It was deduced that energy debt can be offset or paid back within 2.37 years of operation. Meanwhile, the total water economy in the construction of the bioethanol plant amounts to 960,453.44 m^3. Likewise, the whole operation consumed a total of 12,368,904,260.86 L for a year's operation, which is equivalent to 412.30 L water L^{-1} ethanol produced, or 19.45 L MJ^{-1}, or 24,541.48 L T^{-1} cane processed.

Key words: *alternative bioethanol feedstock, commercial scale, energetics, footprint, life cycle analysis, net energy balance, net energy value, water consumption, water economy*

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INTRODUCTION

In the recent years, awareness on the worsening climate condition has raised concerns on how to address the situation. Global warming, although a natural occurrence has been hastened up by anthropogenic emissions. The rapid industrialization has intensely contributed to the buildup of greenhouse gases in the atmosphere, agreed upon by about 97% of the published peer-reviewed scientific journals (*NASA Global Climate Change: Vital Signs of the Planet 2017*). The Intergovernmental Panel on Climate Change (*IPCC 2013*), confirmed that since at least about 1970 until 2010, earth has gained substantial amount of energy. With its Fifth Assessment Report, IPCC reported a physical science basis on the contribution of anthropogenic sources to the global temperature change. Model simulations that fit only the natural influences on the global temperature change cannot explain anymore the trend observed empirically since the 70's, but accounting the anthropogenic emissions on top of the natural causes fit the observed data (*IPCC 2013*). With this, the world is finding out ways to reduce GHG emissions resulting from human activities and keep the earth's temperature rise relative to the pre-industrial period well below the 2°C deleterious limit (*UNFCCC 2014*).

One of the major contributors to the emissions is the transport sector (*Lefevre and Enriquez 2014*) which holds a share of 23% of the world's total GHG emissions (*IEA 2015 as cited by Olivier et al. 2016*) The demand for fuel of the transportation sector has increased substantially in the past decades. In the International Energy Outlook 2016 (*IEO 2016*) reported by the US Energy Information Administration, the transportation sector accounted for the 25% of the total world energy demand in 2012. The demand will continue to increase by 1.4% per annum from 2012 to 2040 (*US EIA 2016*). This projection is dominated by the energy growth contribution of the non-OECD nations which increases by 2.5% per annum as compared to the 0.2% growth of the OECD nations, which have established consuming patterns and are already able to switch to more efficient systems.

Considered a non-OECD nation, the Philippines' gasoline consumption has pumped up from 1.8 B L in 1990 to 4.8 B L in 2015; while diesel on the other hand, has increased from 3 B L in 1990 to 7 B L in 2015 (*DOE, Pers. Comm. January 2016*). But with the COP21 climate campaigners' slogan, "Leave it in the ground," which proposes to limit production of fossil fuels at the coal mine or oil well, renewable fuels is pushed to be the primary source of transportation fuels. The Philippines have effected policies that involve the use of renewable energy to conform with this global movement and to attain energy sustainability. The legislation of the Biofuels Act of 2006 (Republic Act 9367) mandated the use of blended petroleum diesel (with biodiesel) and gasoline (with ethanol) throughout the Philippines. This has encouraged actions to develop and ensure the availability of alternative fuels. One of the projects in the country through the Department of Energy is the National Renewable Energy Program (NREP), which aims to develop strategies that address issues on climate change, energy security, and access to energy. The Renewable Energy Act of 2008 (Republic Act 9513) required the acceleration in the development and utilization of renewable energy by providing fiscal and non-fiscal incentives to investors and equipment manufacturers and suppliers.

The conduct of life-cycle assessment (LCA) of products can be a significant tool to assess the effectiveness of biofuels in terms of its environmental, social, and economic aspects. For instance, a carbon footprint inventory may be conducted to assess the net carbon emission of a process, product, or service such as thermochemical conversion, petroleum refining, biofuel production, drinking cups, computers, remediation techniques, land-use change, and trash disposal to name some (*Gnansounou and Pandey, 2017; NBIS 2008*). A negative net carbon footprint is desired for the mitigation of climate change. However, biofuel production entails accomplishment of several validations before its production and usage gets supported. Aside from carbon, it is also necessary to assess the system if it is economical, reproducible in large amounts without affecting the food supply, provides a net energy gain, and does not exploit too much natural resources, such as water (*Hill et al. 2006*).

This study focused on the energetic life-cycle analysis of the production of bioethanol from sweet sorghum and its water inventory. Bioethanol is a renewable fuel that can be an alternative for gasoline. Feedstocks for bioethanol are classified into three, namely: saccharine; starchy; and cellulosic (*BAA 2016*). Glucose can be extracted from these feedstocks, which is the substrate for fermentation reaction producing bioethanol. The most commonly used saccharine bioethanol feedstock in the Philippines is sugarcane since the country is a large producer of this crop and it is the most readily available (*DOE 2015*). The sugar industry can easily swing between raw sugar manufacture or ethanol production or both depending on economics. More commonly, molasses, which is a by-product in the production of sugar crystals from sugarcane, is utilized both for potable and fuel-grade ethanol. The supply of molasses however falls short of the demand. The supply only averages to about 1 million tons (*DOE, pers. comm., January 2016*) but the demand of fuel grade and potable grade ethanol producers amounts to 1.5 M t. The deficiency opens opportunities to develop alternative feedstock that could complement the gap. Currently, the country is developing the potential of sweet sorghum (*Sorghum bicolor* L. Moench), which is a multi-purpose crop similar to grain sorghum except that it has sugar-rich stalks that may actually increase the country's ethanol production.

Ethanol production from sweet sorghum is promising because it can be grown in a wide range of climatic and soil conditions (*Vermerris et. al., 2015; FAO, n.d.*). It has a very high sugar content, which varies from 15-23°Brix. It is also cheaper to cultivate than sugarcane and is a short duration crop (2-3 cropping season versus 1 of sugarcane) (*Alibuyog 2011*). Moreover, sweet sorghum can thrive in dry land as it is more adaptive to drought and it requires less water (*Benitez 2011*). According to the International Crops Research Institute for the Semi-Arid Tropics (*ICRISAT 2007*), sweet sorghum requires one-eighth the amount of water compared to sugarcane and about half that corn requires. It has a lot of potential as a major feedstock for ethanol production because of its competitiveness with other feedstocks such as sugarcane and cassava. The grain from its earhead is used as a food/feed source. The juice from its stalks can be used for the production of jaggery and syrup and could primarily be a source for ethanol. The bagasse (leftover stalks after juice extraction) and green foliage can be used for cogeneration of power, animal feeds and organic fertilizer or for paper manufacturing.

The main issue of biofuel production however, is the water consumption. According to *Hoekstra and Chapagain* (*2008*), biomass production is the greatest water consumer. The global agricultural production of biomass, for food and fiber alone, constitutes about 86% of worldwide freshwater use. Water footprint of energy from biomass can even be 70 to 700 times larger than from fossil fuels (*Gerbens-Leenes et al. 2009*).

Bioethanol from sweet sorghum has been proven by previous studies as carbon neutral (*LAMNET by ICRISAT 2007*) and even carbon negative (*Demafelis et al. 2015*). In this study, the energy balance and water requirement of bioethanol production from sweet sorghum was determined based on a 30-million-liter-per-year (MLPY) commercial scale production. Net energy gains was quantified, along with the total volume of water needed, for the whole operation to assess the practicability of the production of bioethanol from sweet sorghum. The energetics and water requirement in the construction of the bioethanol plant, and the energetic payback period were likewise assessed.

MATERIALS AND METHODS

The energy balance included both the electric and thermal flow within the whole system from cradle-to-grave. The boundary begins from the cultivation of sorghum seeds to ethanol production up to the products use (**Figure 1**). The inventory considered the total requirements for fuel, electricity, and heat; and the "embodied energy" of the chemicals and materials used in the construction of equipment and buildings, and in the plantation and the processing plant. Embodied energy is defined as the energy spent during the life-cycle of a material, as used also by US Department of Energy (*USPA 2015*).

Initially, the material balance was established that enabled determination of daily capacity to achieve the 30 MLPY commercial scale bioethanol production, the mass flow rates in every process, and eventually the energy balances, equipment design, and plant layout necessary to estimate construction materials. It was assumed that the milling section operates for 165 d yr^{-1}, which considers the plantation schedule of sweet sorghum, and produces enough syrup to run the downstream processes of producing bioethanol for 270 days. From this, the total plantation area was estimated from the assumed yield, and then the agricultural inputs were determined.

This study focused on the total energy expended during the production and the total energy gained that comes from the products of the whole system – power from bagasse and biogas, and biofuel, along with the energetic payback time. The energetic payback time was also computed. Conversely, the total amount of water consumed in the construction and in the production of ethanol was quantified. The ethanol plant was designed to have a co-generation facility and a wastewater treatment facility using aerobic digester.

Energy Balance

All of the materials utilized are converted to equivalent energy in MJ by using the energy factors per amount of material (**Table 1)**. The conversion factors were obtained from the Inventory of Carbon & Energy (ICE) Version 2.0 (*Hammond and Jones 2011*), the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

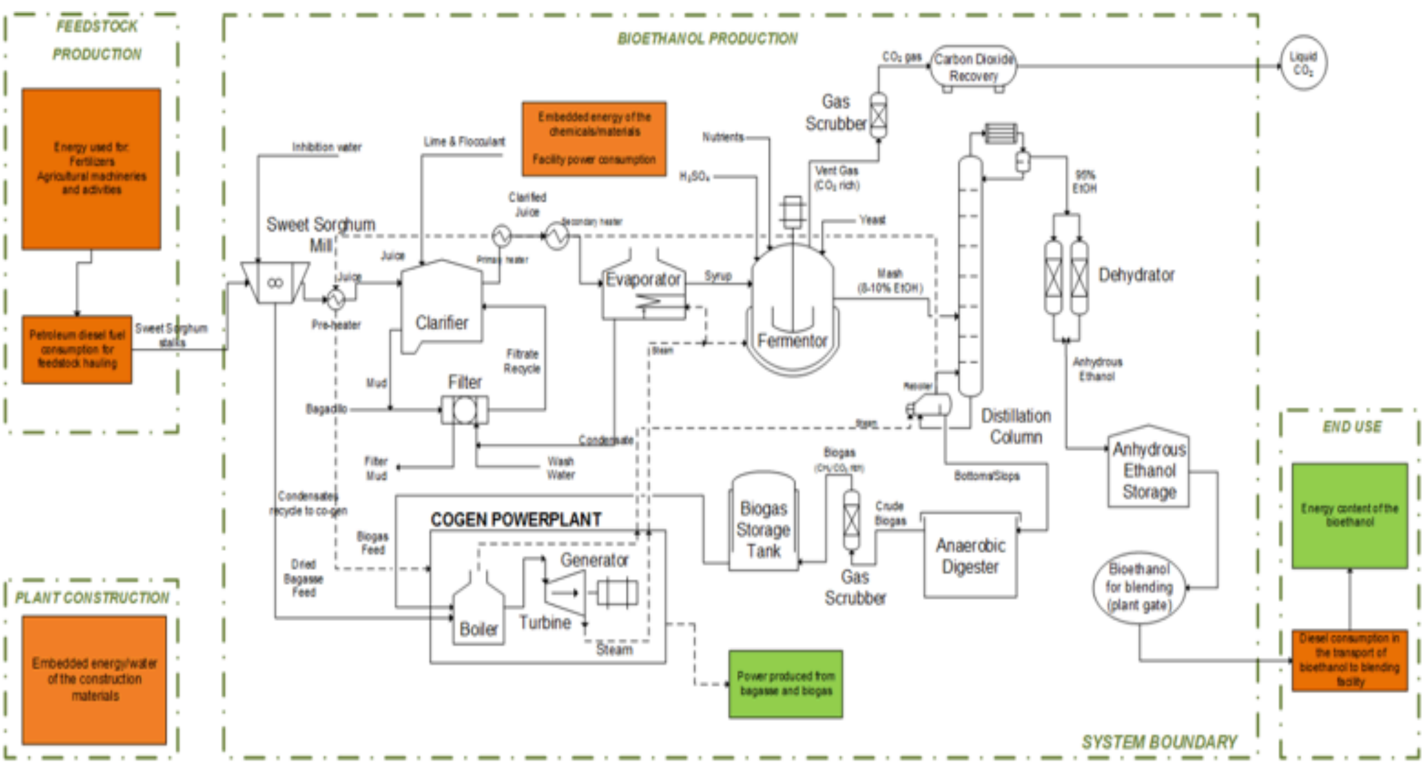

Figure 1. System boundary for the cradle-to-grave assessment of bioethanol production from sweet sorghum.

Table 1. Energy factors used in the assessment of life cycle analysis of bioethanol production from sweet sorghum.

Item	Energy Factor	Reference
Construction	**MJ kg^{-1}**	ICE v. 2.0
Stainless Steel	56.7	
Concrete	1.11	
Steel	20.1	
Concrete Block (Hollow Block)	0.81	
Cement Mortar (1:3)	1.33	
Cement (General-Typical)	4.6	
Sand (dry, ρ=1602 kg m^{-3})	0.005	
Gravel (dry, ρ=1362 kg m^{-3})	0.017	
Galvanized Iron Sheet	22.6	
Field		
Fertilizer utilization (seed crop)	**MJ kg^{-1}**	
P_2O_5	22.19	*GREET 2014*
K_2O	9.02	*GREET 2014*
Nitrogen	62.96	*GREET 2014*
Urea	31.89	*GREET 2014*
Diesel Consumption	43.41 **MJ L^{-1}**	*GREET 2014*
Factory[2]	**MJ kg^{-1}**	
Lime (Calcium oxide, CaO) from clarification	5.37	*GREET 2014*
Sulfuric Acid (H_2SO_4)from fermentation	0.65	*GREET 2014*
$MgSO_4$	8.28	*GREET 2014*
Urea	31.89	*GREET 2014*
Di-Ammonium Phosphate (DAP) from fermentation	19.16	*GREET 2014*
Biocide	120.00	*Moghimi et al. 2014*
Yeast (*Saccharomyces cerivisiae*)	43.00	*GREET 2014*

2014 (*GREET 2014*) by *Argonne National Laboratory* (*2014*), *Moghimi et al. 2014*, and *GREET* (*2013*). Argonne's GREET life cycle model provides a complete embodied energy information on a wide variety of materials including process inputs for feedstock production, transport, ethanol plant operation, fuel delivery, and vehicle operation. The components that the GREET model can calculate includes two routes: 1) the Well-to-Pump (WTP), which accounts all the energy emissions to produce the material and 2) the Well-to-Wheels (WTW), which then includes end-use of the materials using different vehicle techonology. In this study, the WTP route was used in the calculation.

The term "energy expenses" was used in the text to denote components that consume energy. The energy gains and the energy expenses were combined to obtain the net energy of the system.

Construction. The energetics in the construction of the bioethanol plant included all the embodied energy and conveyance of the construction materials used in the fabrication of the equipment, the assembly of the facilities, and additional footing. The bill of materials for the construction of the facility includes components for the roofing system, wall and framings, flooring, beams and girders, staircases, hand railings, and bracings while theassembly of the equipment in the plant includes base support, pipes and pumps. For this assessment, it was assumed that the materials were transported by a heavy-duty truck with a hauling capacity of 10 tons and fuel economy of 2.126 km L^{-1} diesel (*GREET 2013*) from a 150-km distance. The total energy expended in this level was considered as "energy debt" and was used to compute for the "payback period" or the amount of time it will take for the energy gains, if there will be any, during the production to compensate the debt.

Plantation. The first level of operation was from the plantation. It was assumed that 8 kg sorghum seeds were planted per ha (*Reddy et al. 2011*). Two croppings were considered – seed crop and ratoon, which can yield a total of 100 T ha^{-1} yr^{-1}, within a period of 3-4 months, sweet sorghum can produce as average of 50 T ha^{-1} stalks based on the statement of the *National Economic and Development Authority* (*2014*) that within a period of 3-4 months, sweet sorghum can produce an average of 50 T ha^{-1} stalks. Based from this yield, the total plantation area that can produce sufficient daily ton cane requirement was computed.

The energy balance in the plantation was contributed by the fuel requirements of the agricultural activities and the embodied energy of the fertilizers utilized (**Table 2**). Some of the diesel requirements for the agricultural operations were obtained from sugarcane practices by *Macedo et al.*

Table 2. Agricultural inputs and diesel requirements of a sweet sorghum plantation.

Sweet sorghum seeds, kg ha^{-1}	Amount
Fertilizer utilization[1] (seed crop), kg ha^{-1}	
P_2O_5	70
K_2O	70
Nitrogen	70
Urea	150
Fertilizer utilization[1] (ratoon), kg ha^{-1}	
P_2O_5	35
K_2O	35
Nitrogen	35
Urea	75
Diesel Consumption	
Plant cane[1], L ha^{-1}	52
Harvester[2], L tc^{-1}	0.986
Loader[2], L tc^{-1}	0.171
Tractor hauler/transloader[2], L tc^{-1}	0.395
Other activities[2], L ha^{-1}	67

(*2008*) since the same equipment were assumed to be used for sweet sorghum. Other data were sourced from the local studies conducted by *Demafelis et al.* (*2013*).

Immediately after harvesting, the sorghum canes were transported to the factory. The plantation distance to the factory was assumed to be 10 km. Hauling is done by means of a heavy-duty truck with 10 T capacity and a fuel economy of 2.126 km L^{-1} diesel (*Argonne National Laboratory 2014a*), which is also translated to its equivalent energy and included in the inventory.

Factory. The conversion of canes to ethanol undergoes several procedures. When the trucks enter the factory, they were weighed and then queued up or directed straightaway to the start of the operation. The trucks are tipped and the canes fall to the carriers passing through leveler, knives, and shredder and then delivered to the milling section. The prepared canes were milled and juice was extracted at 93.91% Pol extraction efficiency. The mixed juice then undergoes clarification by hot liming. Clarification was carried out at 76°C, which requires the use of a heater before liming. The mud produced from the clarifier was collected and transported back to a composting facility near the plantation using a heavy-duty truck. The clarified juice was then pre-heated to 93°C before finally heating to 105°C before it enters the quadruple-effect evaporator and achieves syrup at 65°Brix. The heaters use up steam at 150°C and 4.76 bar, while the evaporator uses steam at 120°C and 1.98 bar.

Before fermentation, the syrup is diluted to 18°Brix. The diluted syrup is then fermented using *Saccharomyces cerevisiae*. The CO_2 released during fermentation is collected and the yeast is recovered at 80% (w/w yeast) efficiency. The products were distilled and the hydrous ethanol recovered is dehydrated. The reboilers of the distillation column use 220°C steam at 4.76 bar. The procedure produces ethanol with 99.94% purity. The wastewater generated was digested in an anaerobic digester and the biogas was collected and used for power generation. The bioethanol was then transported to the blending facility by a truck with a 20,000 L capacity and fuel economy of 2.126 km L^{-1}. Distance is assumed to be 150 km. The factory operates for 24 hrs a day and a total of 270 days a year (165 days for milling and downstream processes, and 105 days for the downstream processes with the milling section shut down).

The energy balance from the factory included the embodied energy of the materials used for the clarification (calcium oxide), fermentation (yeast, H_2SO_4, $MgSO_4$, Urea DAP, biocide), and the electric and thermal requirements of the processes. For the purpose of energy accounting, the products' equivalent energy content was used to estimate the energy that will be harnessed once they are consumed.

Included in the design of the factory was a co-generation facility, which uses bagasse as fuel for boiler. The boiler operates at 67 bar and 510°C. The sweet sorghum bagasse has a heating value of 9,071.4 kJ kg^{-1} (*Golder Associates 2011*). The steam requirement of the industrial activities is extracted from the steam leaving the turbine of the co-generation facility. To provide the 220°C steam to the reboilers, a stream of high-pressure steam was extracted from the turbine at 400°C and 45 bar and it was mixed in a steam header with the low-pressure steam at 120°C and 1.985 bar. The steam leaves the reboiler at 150°C and 4.76 bar, which is utilized by the heaters. The remaining low-pressure steam are condensed and are collected together with other condensates that could be fed to the boiler again. The temperature of the condensing water was assumed at 25°C. Some bagasse from milling were reserved for the rest of the operation period even after the mill was shut down.

Payback Period. The payback period, defined earlier, was computed by dividing the energy debt by the "net energy gain" (NEG). The net energy gain was computed by summing up all the energy gained from the products of the process (bioethanol and power) and subtracting the energy expended during the operation (diesel consumption, materials used, electricity use).

$$\textit{Payback Period} = \frac{\textit{Total energy debt}}{\textit{NEG}} * 270\ \textit{days} \qquad \text{(Equation 1)}$$

Where:

Total energy debt = Energy expended in the construction of the facility plus the transport cost in delivering the materials

NEG = Energy Gained – Energy Expended

Water Requirement

The total water requirement was quantified for the given system boundary. In the plantation, 10,000 m^3 ha^{-1} was used for irrigation (*Reddy et al. 2011*). In the factory, water inventory focused on the requirements of the mill (for imbibition), the clarification process for the preparation of the milk of lime (MOL), water for the dilution of the syrup before fermentation, the boiler of the cogeneration facility, condensing water, and for washings. Some water was recycled as in the first two evaporators of the quadruple-effect evaporator, the condensates from the heaters and reboilers, and the recirculating amount of unused exhaust steam from the turbine. The condensates from the processes were collected and make up water was added to achieve a final temperature of 95°C. The water was cooled to 90°C using air-cooling tower before being pumped to the boiler again. A make-up water equivalent to 10% of the working water volume of the boiler was assumed to account for the boiler blowdown.

Additionally, the concept of embedded water, as with the embedded energy, was employed. This was used during the construction of the facility and fabrication of equipment, which used materials that have their inherent water footprint. After designing and lay-outing the whole facility, the bill of materials was estimated. By determining the total amount of construction materials, conversion factors were used: 2,000 L ton-concrete^{-1} (also applied for gravel); and 40,000 L ton-steel^{-1} (also applied for stainless steel and galvanized sheet) (*Zygmunt 2007*) for the water requirement of the system, without classifying the type of water as blue, green, or grey. The final values are reported in MJ-expended L-ethanol^{-1}, MJ-gained L-ethanol^{-1}, and L-water L-ethanol^{-1}.

RESULTS AND DISCUSSION

Energetics of the Pre-Operational Period

Construction. The values were computed based on the amount of materials used in the structure, equipment, footing, and piping of the different divisions of the facility: divisions that require roofing and steel (process water R.O. unit, the milling section, the pre-treatment, fermentation, cogeneration facility, CO_2 recovery, cooling tower, and tank farms), divisions that require roofing and concrete wall (administration building, the bagasse shed storage, the canteen, clinic, fire station area, laboratory, and warehouse), and divisions that do not require roofing and wall but base only (loading and unloading area, parking, facultative lagoon, and roads) (**Table 3**). The total energy expended during the pre-operational period amounts to 1,045,158,800.32 MJ or a total of 34.84 MJ L-ethanol^{-1} (basing on the designed capacity of the processing plant).

With the total bill of materials, the number of trips required to bring the materials to the site was computed using the 10-ton capacity truck. A total of 36,408 trips was calculated which translates to 81,917,444.43 MJ or 2.73 MJ L^{-1} ethanol. The sum of the values equivalent to 1,127,076,244.75 MJ or 37.57 MJ L^{-1} ethanol was considered the carbon debt.

Energetics for the Operational Period

Plantation. After the computation of material balance, the daily required capacity was computed to be 3,050 T sorghum cane d^{-1} for the 165 days milling operation. This capacity translates to a plantation area of 5,032.5 ha following the total annual yield of 100 T ha^{-1}.

In the plantation, energy expended was the sum of the embodied energy of fertilizers used for the total plantation area during seed cropping and ratoon, and of the petroleum diesel consumed by the machines and other field activities. Diesel consumption in planting the canes, harvesting, loading, transloading, and other activities constituted the most energy expense contribution by 41.10% (59,908,703.37 MJ yr^{-1} or 2 MJ L^{-1} ethanol) of the total (145,772,756.63 MJ yr^{-1} or 4.86 MJ L^{-1} ethanol) (**Table 4**). It was immediately followed by the energy expenses in utilizing fertilizers (P_2O5, K_2O, nitrogen, and urea) during seed cropping with 39.27% (57,242,702.17 MJ yr^{-1} or 1.91 MJ L^{-1} ethanol) and

Table 3. Energy inventory during the pre-operational period.

Component	Material, ton					Equivalent Energy, MJ	Equivalent Energy, MJ L^{-1} ethanol
	Galvanized Sheet	Steel	Concrete	Stainless Steel	Gravel		
Structural	169.70	5,178.13	5,018.01	142.87		311,105,947.78	10.37
Equipment		4,870.56				276,160,923.30	9.21
Footing		5,728.50	100,532.14	223.46	45,572.49	449,841,447.30	14.99
Piping		141.98				8,050,481.94	0.27
TOTAL	169.70	15,919.18	105,550.15	366.33	45572.48595	1,045,158,800.32	34.84

Table 4. Energy contribution of the activities in the plantation.

Item	Energy expended, MJ year^{-1}	Energy expended, MJ L^{-1} ethanol	Percentage
Sweet sorghum seeds, kg ha^{-1}			
Fertilizer utilization (seed crop), kg ha^{-1}			
P_2O_5	7,815,857.49	0.26	5.36
K_2O	3,179,056.11	0.11	2.18
Nitrogen	22,178,217.74	0.74	15.21
Urea	24,069,570.83	0.80	16.51
Subtotal	57,242,702.17	1.91	39.27
Fertilizer utilization (ratoon), kg ha^{-1}			
P_2O_5	3,907,928.75	0.13	2.68
K_2O	1,589,528.06	0.05	1.09
Nitrogen	11,089,108.87	0.37	7.61
Urea	12,034,785.42	0.40	8.26
Subtotal	28,621,351.09	0.95	19.63
Diesel Consumption			
Plant cane, L ha^{-1}	11,361,242.07	0.38	7.79
Harvester, L tc^{-1}	21,542,662.85	0.72	14.78
Loader, L tc^{-1}	3,736,100.76	0.12	2.56
Tractor hauler/transloader, L tc^{-1}	8,630,174.26	0.29	5.92
Other activities, L ha^{-1}	14,638,523.43	0.49	10.04
Subtotal	59,908,703.37	2.00	41.10
TOTAL	145,772,756.63	4.86	100.00

then by the fertilizers during the ratoon cropping with half of the initial at 19.63% (28,621,351.09 MJ yr^{-1} or 0.95 MJ L^{-1} ethanol).

Hauling. The transport of sorghum canes from the field to the factory also consumes diesel. In this case, it was assumed that the factory was located 10 km away from the plantations. The total amount of diesel needed to transport 503,250 T of cane annually amounted to 1,183,719.49 L yr^{-1}, which was equivalent to an energy expenditure of 51,391,049.10 MJ yr^{-1} or 1.71 MJ L^{-1} ethanol.

Factory. The energy expenses in the factory involve those from the embodied energy of the chemicals added for liming and fermentation and from the total energy consumption of the factory during the operation (**Table 5**). The energy expenditures in the factory were contributed prominently by the power consumption, rated at 4.376 MW, that translates to 102,083,328 MJ yr^{-1} (3.40 MJ L^{-1} ethanol), which is 95.45% of the total (106,947,290.98 MJ yr^{-1} or 3.56 MJ L^{-1} ethanol). This was followed by the materials for fermentation at 3.28% (urea 1.71%; DAP 0.52%; $H_2SO_4$0.43%; biocide 0.43%; $MgSO_4$ 0.10%; *Saccharomyces cerivisiae* 0.07%), and by lime (for clarification) at 1.26%.

Steam was used to heat the juice, to perform hot liming, to evaporate the juice and form syrup, and to distill the alcohol. All of the steam requirements were obtained from the system, hence not incurring additional energy expense and is therefore not included in the computation of the NEG (**Table 6**). The steam requirements affected the water requirements inventory because some are recycled and condensing water was used up to condense and cool down the steam.

Net Energy Gain (NEG). The net energy for the system was computed to verify if the production of ethanol from sorghum is valuable. The total energy equivalent of the products– power, and ethanol, amounts to 784,328,211.02 MJ year^{-1} (26.14 MJ L^{-1} ethanol) (**Table 7**). The total energy expended in the whole process amounts to 308,706,421.52 (10.29 MJ L^{-1}), which equates to an energy gain amounting to 475,621,789.51 MJ yr^{-1} or 15.85 MJ L^{-1} ethanol produced. The energy obtained from the production of bioethanol from sorghum is 254.07% more than what is consumed, hence acquiring a positive net energy balance, indicating a net energy gain. The carbon debt accumulated from the pre-operational period can therefore be offset or paid back.

Payback Period. With the energy gains, the system can compensate the energy invested in putting up the facility. The payback period was computed by dividing the energy debt accumulated during the pre-operational period (1,127,076,244.75 MJ) and the NEG (475,621,789.51 MJ) during the operations (Equation 1). It was computed that the debt can be compensated after about 640 days of operation (2.37 years).

Water Requirement

The water requirement of the boundary system was

Table 5. Energy contribution of the activities in the factory (bioethanol from sweet sorghum).

Item	Amount kg yr^{-1}	Energy expended MJ yr^{-1}	Energy expended MJ L^{-1} ethanol	Percentage %
Lime (Calcium oxide, CaO)	251,625.00	1,351,816.33	0.05	1.26
Sulfuric Acid (H_2SO_4)	703,572.03	457,718.92	0.02	0.43
$MgSO_4$	13,530.23	112,089.00	0.00	0.10
Urea	57,986.71	1,848,935.41	0.06	1.73
Di-Ammonium Phosphate (DAP)	28,993.35	555,628.77	0.02	0.52
Biocide	3,865.78	463,893.64	0.02	0.43
Yeast (*Saccharomyces cerivisiae*)	1,718.13	73,880.91	0.00	0.07
Electricity Use (MWh yr^{-1})	28,356.48	102,083,328.00	3.40	95.45
TOTAL		106,947,290.98	3.56	100.00

Table 6. Steam requirement and process parameters in a 30 MLPY-capacity sweet sorghum bioethanol facility.

Component	Amount of Steam, kg hr^{-1}	Steam Inlet		Steam Outlet	
		Operating T, °C	Operating Pressure, bar	Operating T, °C	Operating Pressure, bar
Milling					
Pre-heater (before liming)	6,279.02	150	4.76	130	2.70
Primary heater (before evaporator)	2,981.76	150	4.76	130	2.70
Secondary heater (before evaporator)	2,104.77	150	4.76	130	2.70
Evaporation					
Evaporator (entering steam) – Calandria 1	28,442.05	120	1.98	110	1.435
Evaporator – Calandria 2		110	1.435	99.35	0.980
Evaporator – Calandria 3		99.35	0.980	84.64	0.566
Evaporator – Calandria 4		84.64	0.566	51.00	0.136
Distillation					
Primary Column – Reboiler	27,475.39	220	4.76	150	4.76
Dealdehyde Column – Heater 1	252.04	150	4.76	131	4.76
Dealdehyde Column – Heater 2	121.24	150	4.76	121	4.76
Dealdehyde Column – Reboiler	6,072.66	220	4.76	150	4.76
Rectifying Column – Reboiler	4,842.04	220	4.76	150	4.76
Molecular Sieve Dehydration Unit (MSDH) – Heater 1	103.8	150	4.76	130	4.76
MSDH – Heater 2	103.2	150	4.76	140	4.76
MSDH – Heater 3	51.73	150	4.76	143	4.76

Table 7. Energetics of the bioethanol production from sweet sorghum.

Item	Energetics	
	MJ yr^{-1}	MJ L^{-1} ethanol
Expenditures		
Plantation	145,772,756.63	4.86
Transportation (plantation to factory)	51,391,049.10	1.71
Plant Operation	106,947,290.98	3.56
Delivery (factory to composting facility)	4,595,324.81	0.15
Subtotal	308,706,421.52	10.29
Products		
Electricity Produced	79,277,331.02	2.64
Methane	69,050,880.00	2.30
Bioethanol	636,000,000.00	21.20
Subtotal	784,328,211.02	26.14
Net Energy	475,621,789.51	15.85

Table 8. Water footprint in the construction of bioethanol plant.

Structure	Material, ton					Water volume, m^3	Water volume, m^3 L^{-1} ethanol
	Galvanized Sheet	Steel	Concrete	Stainless Steel	Gravel		
Structural	169.70	5,178.13	5,018.01	142.87		229,663.98	0.01
Equipment		4,870.56				194,822.52	0.01
Footing		5,728.50	100,532.14	223.46	45,572.49	530,287.58	0.02
Piping		141.98				5,679.35	0.00
TOTAL	169.70	15,919.18	105,550.15	366.33	45572.49	960,453.44	0.03

Table 9. Water consumed in the production of ethanol from sweet sorghum.

Source	Volume of water required (L)	Volume of water per volume of ethanol (L L^{-1})	Volume of water per energy content of ethanol (L MJ^{-1})	Volume of water per ton cane processed (L tc^{-1})
Plantation	50,325,000.00	1.68	0.08	99.85
Imbibition	241,560,000.00	8.05	0.38	479.29
Liming	4,758,000.00	0.16	0.01	9.44
Dilution	219,993,198.01	7.33	0.35	436.49
Co-generation facility	409,900,540.22	13.66	0.64	813.29
Condensing water	11,903,920,720.64	396.80	18.72	23,618.89
Washings	2,259,592,500.00	75.32	3.55	4,483.32
TOTAL	12,368,904,260.86	412.30	19.45	24,541.48

estimated to compare its water usage to fossil fuel. Again, using the total bill of materials, the conversion factors of 2,000 L ton^{-1} concrete (also applied for gravel); and 40,000 L ton^{-1} steel (also applied for stainless steel and galvanized sheet) were used. The total water requirement for the construction amounts to 960,453.44 m^3 or 0.03 m^3 L^{-1} ethanol (**Table 8**). Water usage was contributed mainly by the materials for footing (56%), followed by 25% for structures, equipment (18%), and piping (1%).

From the total amount of available bagasse from the mill amounting to 762,500 kg d^{-1}, the flowrate of the steam was determined (**Table 9**). Boiler steam requirement amounted to 1,666,036.61 kg d^{-1} for the first 165 days and 930,864.90 kg d^{-1} for the rest of the 105 days. The steam is heated to 510°C and power was extracted in the turbine. After extraction, some of the steam circulated to the other processes of the facility, providing enough heat supply. The clean condensates were collected and recycled back to the cogeneration facility. The steam not used for the other processes was condensed using condensing water, adding up to the water requirement of the cogeneration facility. Furthermore, a boiler blowdown of 10% was also accounted.

All in all, the water requirement computed based from the material balance involved water usage for irrigation of the whole plantation, for imbibition (milling), for liming, for dilution of syrup, for boiler, for condensing, and for washing (**Table 9**). Recycled water was used for imbibition, dilution, and washings thereby not adding to the total. The total volume of water used amounted to 12,368,904,260.86 L yr^{-1} operation, which was equivalent to 412.30 L water: 1L $ethanol^{-1}$ produced, or 19.45 L MJ^{-1}, or 24,541.48 L ton^{-1} cane processed.

CONCLUSION AND RECOMMENDATIONS

Evidently, the whole system produces more energy than what it consumes in the process similar to the positive results obtained by *Nasidi et al.* (*2010*) that conducted energy balance of sweet sorghum in Nigeria and *Monti and Venturi* (*2003*) in Italy. Compared with molasses, which is currently the primary feedstock of the Philippines for bioethanol production, *Nguyen et al.* (*2008*) of Thailand reported a positive net energy of 5.95 MJ L^{-1} ethanol produced. The result of the study delivers a higher value at 15.85 MJ L^{-1}, which can make it a better option for bioehtanol production. Another study by *Khatiwada and Silveria* (*2009*) reported a net energy balance ratio of -13.05 MJ L^{-1} for molasses-based ethanol. Moreover, compared with corn, which is being primarily utilized as feedstock for bioethanol production around the globe, the net energy balance ratio (energy output over energy input) of sweet sorghum assessed in this study, which amounted to 2.54, is higher than the energy ratios of producing corn ethanol, which ranged from 1.30 – 1.67 (*Morey et al. 2006*).

Today, our country faces the need for alternative feedstocks for bioethanol production since we are short of the amount to supply for the total domestic demand. Moreover, since we use sugarcane and molasses mainly for bioethanol production, the prices of these products increase, hence the search for an alternative feedstock that will ease the burden of the increasing price of these commodities is conducted. Appropriately enough, this study affirms the use of sweet sorghum for bioethanol production since the energetics study achieved optimistic benefits.

However, assessing the water requirement of the process could gain a veto vote. *Wu and Chiu* (*2011*) reported that on the average, petroleum gasoline production consumes about 2.8 to 6.6 (v/v) water:gasoline ratio. The value obtained from this assessment gave a ratio equal to 412.30 (v/v). This tremendous amount of water requirement should be deliberated if the biofuel system is to be pursued and ways to significantly reduce the water consumption of the process should be found. The result was even smaller than the result of *Nasidi et al.* (*2010*), who attained 2,800 L water:1 L ethanol production. The findings are consistent with previous observations that production of fuel from biomass really consumes more water than from fossils.

If use of wastewater would be accepted for the plantation, then the problem on the enormous water requirement of the process may be addressed. Going further, since the carbon emissions and energetics of the process have been studied and resulted positively, financial deliberations and other market hurdles should now be measured so that promotion of bioethanol production from sweet sorghum for commercialization may be strengthened.

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