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Net energy analysis of sugarcane based ethanol production

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ABSTRACT

Ethanol is being projected as a renewable future biofuel to be a total substitute for gasoline by policymakers in India. Today it is used in blended form with gasoline. Ethanol in India is produced from sugarcane in distilleries and most of those are integrated with sugar industries. Anecdotal evidence suggests that sugarcane production in India consumes lot of water and for irrigating the crop electricity is consumed. Electricity is produced from fossil fuel mainly coal in India. Quantifying the energy input that goes into sugarcane production and ethanol processing is therefore relevant. This paper reports the findings from field investigations into the energy use practices of sugarcane production in a sugarcane belt of Maharashtra and a study of energy use in sugar industry. Net energy value is reported in MJ per litre of Ethanol and is found to be 40% surplus. Similar studies are reported for Brazilian Ethanol by investigators. The key differences in net energy value in India and Brazil arise from the assumptions regarding cane growing practices including power required in pumped irrigation and fertilizer application per litre of ethanol production. Net energy analysis of biofuels depends on the data assumed by the researchers regarding input of energy use, source of energy, energy value of co-products and land and water productivity of sugar cane. Sensitivity analysis is therefore included to account for all these parameters.

1. Introduction

Ethanol is popular biofuel in India and policy makers are emphasizing blending ethanol with gasoline in larger proportions than what it is being used today. However environmentalists and especially those studying water-energy nexus do not consider ethanol as a renewable biofuel option from the net energy value perspective. In India ethanol is produced in dedicated distilleries from sugarcane. Ethanol can also be obtained as a byproduct from sugar factories via sugarcane-sugar-molasses-ethanol route. Sugarcane industry is an important agroindustry well established in different parts in India especially in sugar belts of Uttar Pradesh, Maharashtra and some regions of South India. Either sugar or ethanol or both ethanol and sugar can be manufactured from sugarcane. When sugarcane is directly converted to ethanol without sugar production biofuel availability would increase multiple times. But the age old fuel versus fodder debate might not make this transition easier though this is an effective route in overcoming the issue of sugar price uncertainty. Ethanol production influencing sugar prices is an evidence of fuel influencing food for sugarcane as the feedstock (Zhang et al., 2010). Alternative feed stocks like agricultural residues for ethanol are proposed thereby resolving the food versus fuel problem. Sugarcane tops, an agricultural residue, was studied to assess its potential as a feedstock for bioethanol production (Sherpa et al., 2022) Research on second generation ethanol is widely reported (Pandiyan et al., 2019).

The mention of controversy of sugarcane for ethanol on net energy value basis is explained. Sugarcane in India is grown in irrigated belts. Sugarcane and corn are both water and energy intensive. Literature on net energy analysis of ethanol with corn as a feedstock cites positive or negative energy balance. Corn based ethanol in United states required 29% more fossil energy than what it contributed as fuel according to a study by Pimentel and Patzek, 2005. Another researcher (Shapouri et al., 1995) argued that increased efficiency in farm production has made the net energy balance of corn based ethanol as positive by 24%.Another updated study on corn based ethanol cite a higher figure of 34% net energy surplus value because of efficiency gain (Shapouri et al., 2005). The negative energy balance of ethanol and subsidy being given to ethanol however continues to be critiqued .Prominent critique of corn based ethanol cited negative balance with a statement that US government invests 1.5 gallons of fossil energy to produce 1 gallon of ethanol and expressed strong reservations against subsidizing ethanol (Pimentel, 2010). These different perspectives might appear confusing. A careful examination however reveals the reasons for such different findings. This difference can be solely attributed to the data and methodology used in arriving at the net energy analysis of ethanol. In India such a study looking at the energy water nexus of ethanol becomes necessary in the context of

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renewed policy emphasis on ethanol by the government of India. Such a study has to be based on field investigations and active engagement with the principal stakeholders in ethanol programmes namely the Indian farmers. The present study is unique in the sense that the data used is directly from the field as explained in the next section on methodology.

Life cycle assessment (LCA) studies have been found to be useful to understand the environmental impact of bioenergy generation (Prasad et al., 2020). Hiloidhari et al. (2021) is a recent study on water, energy and carbon footprint of ethanol from sugarcane. They concluded that electricity has the highest energy return on investment (EROI), lowest carbon and water footprints than ethanol. Pereira et al. (2019) reported the findings from life cycle emission analysis from sugarcane ethanol and compared that with corn ethanol and ethanol from wheat. Batlle et al. (2021) reported economic and environmental assessment of the integrated production of palm oil biodiesel and sugarcane ethanol.

Brazil another prominent developing country which has historically promoted sugarcane as well as ethanol is considered as a role model in India for its ethanol push. Some researchers have reported energy balance and emission data for sugarcane based ethanol in Brazil. For example, Macedo et al., 2008 reported energy analysis and sensitivity analysis for production of ethanol from Sugarcane feedstock and reported greenhouse gas emission involved in production of ethanol. They have presented fossil fuel energy input data involved in ethanol production. Another interesting study on Brazilian ethanol is by Otto et al., 2022. They concluded that the N-fertilizer consumption index was much lower for sugarcane-based ethanol than for corn-based ethanol (0.009 versus 0.04 kg N L^{-1}) and hence Brazilian ethanol is more sustainable product when compared to corn based ethanol from United States. One such study in Indian context was attempted by Shelar et al. (2007). However the data especially on water energy nexus is revisited in this study. After careful examination of the literature following goals were formulated for the net energy value study. An important factor in net energy value of ethanol as reported in the literature is the energy needed for irrigation and for fertilizers to increase the crop yields. This data would vary as per agro climatic conditions and needs to be collected through field investigations. Another factor in net energy value of ethanol is the energy used for harvesting and transport and that used in ethanol production in factory. Energy audit of ethanol processing plants was conducted for estimating the fossil fuel use. This paper reports the findings from the field investigations done by the authors to arrive at the net energy analysis for ethanol obtained from sugarcane grown in Maharashtra region of India.

2. Methodology

The goal of the study is to estimate the net energy value of ethanol derived from sugarcane in the prominent sugarcane growing region of Maharashtra, India. Novelty of the study is it uses primary data and measurement done by the authors. The research is targeted at policy makers in India who are promoting ethanol as a substitute in internal combustion engines. The study could be of interest to wide audience including those having stakes in sugar industry, farmers, environmentalists and policymakers. This paper follows the net energy analysis method recommended by Klass (1998).In this method the fossil fuel input is quantified by considering all the inputs from farm to factory and expressed per unit of ethanol. Energy content of ethanol is the output .The arithmetic difference gives us the net energy balance .Field investigations of sugarcane farms were key component in obtaining data used in this analysis. The system boundary chosen for farm to factory energy analysis is as shown in Fig. 1. The mathematical model for estimation of fossil energy value is as follows.

The fossil energy input has to be expressed per litre of ethanol produced. The mathematical model for this estimation would include cane productivity per acre (P) as well as the processing productivity of ethanol expressed as litres of ethanol per kg of sugar cane processed(C). The fossil energy in irrigation per litre of ethanol (Ei) produced is calculated by Eq. (1) where Ep is the electric energy of pumping in kWh/acre, η_o is the overall efficiency of power plant

$$E_i = \frac{E_p}{\eta_o} * 3600 * \frac{1}{(P * C)} \tag{1}$$

To estimate the fossil energy input in ethanol through fertilizer application route (E_f) the specific energy consumption that goes in the production of nitrogen fertilizer (E_n), Phosphorus (E_p) and Potash (E_k) and the corresponding quantities (X_n, X_p and X_k) of consumption per acre are the inputs in Eq. (2).

$$E_f = \left([X_n * E_n + X_p * E_p + X_k * E_k] * \frac{1}{P * C} \right) \tag{2}$$

The calculation for fossil energy input in farm operations (F_o) is by Eq. (3) where S_p, S_r and S_h are specific fuel consumption for ploughing, rotavator, and harrowing operation respectively in litre per hour and T_p, T_r, T_h are the corresponding time in hours. The calorific value (C_v) of the fuel used has to be known.

$$F_o = (S_p * T_p + T_r * S_r + T_h * S_h) * C_v * [\frac{1}{(P * C)}] \tag{3}$$

Fossil fuel energy in transportation (E_t) of the cane from farm to factory would require data on average distance travelled (D), mileage

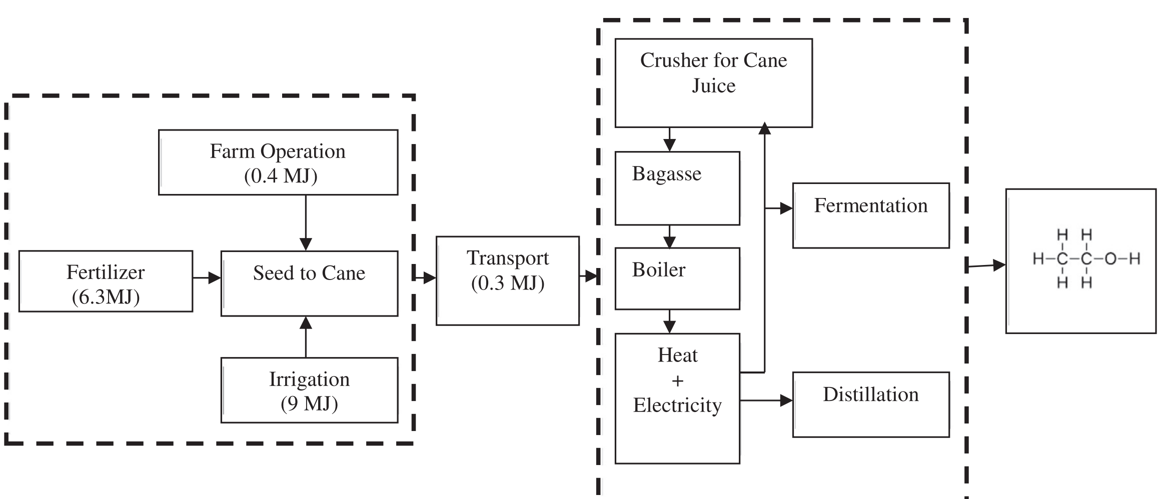

Fig. 1. Farm to factory fossil energy input per litre of ethanol.

of the vehicle (M) and the load carrying capacity of the vehicle (W) Eq. (4) is used for the calculation of energy input per litre of ethanol.

$$E_t = \frac{(D * M)}{(W * C)} \quad (4)$$

3. Case study

Field investigations of sugarcane farms were key component in obtaining data used in this analysis. 100 farmers from Maharashtra region in India were interviewed and average values are used as input. Farmers from Kolhapur, Sangli, Solapur and Nashik region were surveyed. These are the prominent sugarcane growing regions of Maharashtra. All these regions use flood irrigation and tap groundwater .All the surveyed farmers were electrified and used pumps for irrigation. Flood irrigation is practiced for every 10 days so that there are 42 rotations for the crop cycle. 5 Horsepower pump runs for 8 h to irrigate 1 acre of sugarcane during every rotation. The calculations are done assuming overall (fuel to electricity) efficiency of 33%. The energy equivalence of 1 kWh electricity is taken as 3.6 MJ .(Khatiwada and Silveira, 2009) Mathematical model in the Eq. (1) was used for calculation of fossil energy input in irrigating the fields.

The content of fertilizers is expressed in N: P: K ratio. Fertilizer with prominently nitrogen was one third the total quantity.Mathematical model given in (2) was used. The data on electricity consumed for pumping, diesel used in tractors for various agricultural operations and fertilizer application practices from plantation to harvesting was obtained. To quantify the diesel consumption for tillage two in-depth studies were conducted on two farms located in Nashik. Diesel fuelled tractors are used for farm operations. The surveyed farmers used 35 HP tractors. Average specific fuel consumption of tractors is about 0.28 l/kWh. Eq. (3) was used in estimating fossil energy consumption in farm operations. According to farmers it takes about 3 to 4 h for land preparation, cultivation and harvesting per acre. We have assumed the working hours of 3 h for a 35 HP tractor. This works out to be 20 litres of diesel consumption per acre. Some research papers assume a similar figure (Baruah and Bora, 2008).

Cane transportation from farm to factory was done earlier by bullock carts. Recently the cane transport is by diesel trucks and hence fossil fuel consumption for transport is considered. One truck carries 20T of cane and travels a distance of 40 km (to and fro), mileage of truck is considered as 4 km/litre. This data was collected from field study and Eq. (4) was used for calculation.

Some statistics related to energy input required for sugar and ethanol production was collected from energy audit of a sugar mill located in the Nashik district of Maharashtra (India). This mill coproduced ethanol and electricity via cogeneration facility along with sugar. Crushing capacity of the mill in 2018–19 was 4650 tonnes of cane crushed per day and the cane was crushed for 140 days. The cane recovery was reported to be 11.8% with average daily sugar production of 5500 quintals. About 23% bagasse was measured in the cane so that the daily bagasse generated was about 1068 tonnes. Almost all of the bagasse was consumed in-house as fuel in the steam generators. Four steam generators two of capacity 35T/h and the other two with 30T/h and 25T/h operated at a gauge pressure of 21 bar. Turbo generators are rated at 5.75 MW and meet the electrical demand of the industry and ethanol production capacity is 40 kg litres per day. If one ton of sugarcane is crushed in sugar factory the yield is approximately 110 kg of sugar. Moreover the balanced molasses is converted to ethanol and the typical yield is about 10 litres. If only ethanol is produced which means sugar production is sacrificed, then about 76 litre of ethanol is the yield. It is possible to attribute energy content to sugar and perform the energy analysis or assume that the entire cane is converted to ethanol. As our analysis of sugar industry shows, bagasse is the major fuel input and external fossil fuel use is negligible both as a fuel in boiler as well as electric supply from grid. We have therefore assumed fossil energy input for ethanol processing as nil based on our sample study of sugar industry producing sugar and ethanol because bagasse is a major fuel.Net fossil fuel consumption for ethanol production is therefore assumed to be nil. Evacuated tubes and parabolic concentrators can be used to save bagasse in ethanol plants (Anastasovski, 2021).

Klass (1998) mentions the typical values of fossil fuel energy used in fertilizer production and same has been assumed in the study. Capital energy inputs in materials for sugar industry are neglected. Parameters like crop duration, crop productivity, pump capacity and usage, fertilizer inputs and tractor use and its diesel consumption were obtained from investigation are reported in Table 1.

4. Energy return

Farm fossil energy inputs are the key parameters influencing net energy value. Differences in the net energy value can arise due to differences in sugarcane yields, fertilizers and water application practices, method of irrigation, ethanol conversion technologies and fertilizer manufacturing efficiency. Fertilizer application usage in farms influence the sustainability of biofuels like ethanol (Otto et al., 2022)

Our analysis reported in Table 2 highlights the influence of fossil energy input in sugarcane production which negates the renewable energy content of ethanol. About 16 MJ/litre fossil inputs goes in production of ethanol that has energy content of about 22 MJ/litre. Thus our analysis suggests that Ethanol from sugarcane as a feedstock has a positive net energy value. Our analysis further suggests that irrigation as practiced for sugarcane cultivation consumes about 56% of the fossil energy input. About 40% of the fossil energy consumption is due to fertilizer application. About 3% of the fossil energy input is due to the use of mechanized agriculture (tractors) and about 2% for cane transport from farm to factory. Considering that Sugarcane is a water intensive crop its viability as a feedstock for ethanol therefore depends on water use efficiency and hence reduction in energy used for irrigation. It is also observed that the surplus energy per litre of ethanol produced is only 40%. Table 3

Table 1
Data obtained from farmers survey.

Parameters	Data obtained from field	Explanation
Crop cycle	Fourteen months	Fully grown sugarcane stalk
Irrigation schedule	Flood irrigation for every 10 days 42 rotations for the crop cycle.	1 hectare is 2.5 acres, 5 Horsepower pump runs for 8 h to irrigate 1 acre of sugarcane.
Electricity used for water pumps irrigating sugarcane	Electricity is used for pumping water and about 2000 kWh is consumed every acre	We have assumed pump runs continuously at full load. At 85% loading the pump should consume 1700 kWh/acre.
Land Productivity	Every acre thirty two tons of cane	
Energy required for tilling the land and other operations	Every acre of land tilled requires 20 litres of diesel for tractor and other equipments	
Fertilizer application	0.6 ton per acre	Data collected from field survey of 100 farmers. The content of fertilizers is expressed in N: P: K ratio. Fertilizer with prominently nitrogen was one third the total quantity. About 0.1 ton of fertilizer each with N: P: K ratio as 18:46:36 and 10:26:26 was applied. The balance had a N:P:K ratio as 19:19:0

Table 2
Net Fossil Energy Analysis per litre of Ethanol.

Parameter	Energy value (MJ per Litre)	% of Energy	Comments
Energy for irrigating sugacane	8.97	56.06	Pumping energy. The calculations are done assuming overall (fuel to electricity) efficiency of 33%. The energy equivalence of 1 kWh electricity is taken as 3.6 MJ
Fossil fuel energy input for Fertilizers	6.3	39.37	Data on energy required for production of Fertilizers using the figures cited by Klass (1998). Fossil input will be more for less efficient Indian Fertilizer Industries.
Energy input for farm operations	0.4	2.50	Diesel required for ploughing, etc.
Energy for Transport (farm to factory)	0.3	1.87	One truck carries 20T of cane and travels a distance of 40 km (to and fro), mileage of truck is considered as 4 km/litre.
Energy input in ethanol processing	0	0	Capital energy inputs in materials for sugar industry neglected. Energy input for ethanol processing is assumed zero because bagasse is the major fuel.
Fossil energy input to ethanol	16	100	
Energy content available in ethanol	22		
Net energy value of ethanol	6		Energy surplus

Table 3
Comparison of Net Fossil Energy Analysis of Ethanol for Brazil and India.

Parameter	India (Current study) MJ/litre	Brazil (Mecado et al., 2008) MJ/litre
Energy for pumping water in farm	8.97	Negligible since rainfed
Fossil fuel energy input for fertilizers and farm operations	6.7	2.63
Energy for Transport (farm to factory)	0.3	–
Energy input in ethanol processing	0	0.66
Fossil energy input to ethanol	16	3.29
Energy content available in ethanol	22	22
Net energy value of ethanol	6	18.71

Table 4
Net Fossil Energy Analysis of Ethanol and its variation with irrigation energy use.

Parameter	Average scenario of irrigation	Increase of irrigation energy by 25%	Increase of irrigation energy by 50%
Energy for pumping water in farm expressed as per litre of ethanol	8.97 MJ	11.21 MJ	13.45 MJ
Fossil fuel energy input in fertilizers used in cane production expressed as per litre of ethanol	6.3 MJ	6.3 MJ	6.3 MJ
Fossil energy (Diesel) in tractors used in sugarcane fields expressed as per litre of ethanol	0.4 MJ	0.4 MJ	0.4 MJ
Energy for Transport (farm to factory)	0.3 MJ	0.3 MJ	0.3 MJ
Total Fossil energy input to ethanol expressed as per litre of ethanol	16 MJ	18.21 MJ	20.45 MJ
Energy content available in one litre of ethanol	22 MJ	22 MJ	22 MJ
Net energy value of ethanol	6 MJ/litre	3.79 MJ/litre	1.55 MJ/litre

Table 5
Net Fossil Energy Analysis of Ethanol and its variation with fertilizer use.

Parameter	Average scenario of productivity	Increase in productivity by 25% by increasing fertilizer use by 25%	Increase in productivity by 50% by increasing fertilizer use by 50%
Production of sugarcane per acre	32 Tons	40 Tons	48 Tons
Energy for pumping water in farm expressed as per litre of ethanol	8.97 MJ	7.18 MJ	5.98 MJ
Fossil energy supplied in fertilizers applied to sugarcane expressed as per litre of ethanol	6.3 MJ	7.87 MJ	9.45 MJ
Fossil energy (Diesel) in tractors used in sugarcane fields expressed as per litre of ethanol	0.4 MJ	0.4 MJ	0.4 MJ
Energy for Transport (farm to factory)	0.3 MJ	0.3 MJ	0.3 MJ
Total Fossil energy input to ethanol expressed as per litre of ethanol	16 MJ	15.75 MJ	16.13 MJ
Energy content available in one litre of ethanol	22 MJ	22 MJ	22 MJ
Net energy value of ethanol	6 MJ/litre	6.25 MJ/litre	5.87 MJ/litre

compares net energy analysis of current study with the data reported for Brazil by Macedo et al., 2008. It is seen that the net surplus energy obtained for Brazil is substantially higher (18.71 MJ/ litre as against 6 MJ/ litre obtained in current study). This is due to the fact that the sugarcane cultivation being rainfed, its irrigation energy demand is negligible (Hernandes et al., 2014). Irrigation energy is a major element in total energy required in ethanol production in Indian context. The fertilizer consumption is also lower in Brazil (Scarpare et al., 2016) Lower values of fertilizer consumption in Brazil are also cited by an in-depth study on fertilizer application by another researcher (Otto et al., 2022).

5. Sensitivity analysis

Agriculture inputs like fertilizer, energy and fuel use are the major causes for differences in calculated net energy value and carbon footprint for sugarcane (Pereira et al., 2019). Agricultural inputs vary with agro climatic regions as explained in Holmatov et al. (2019).Sensitivity analysis is reported to capture this variation. Analysis done accounts for the increase in irrigation energy use, increase in fertilizer inputs and productivity improvement. . To understand to what extend these parameters influence the net energy analysis, sensitivity analysis was attempted. The basis of sensitivity values are data from the fields and discussion with agricultural scientists Table 4 indicates that in event of increase in irrigation energy inputs by 25% and 50% the net energy content of ethanol changes from 6 MJ/litre to 3.79 MJ/litre and 1.55 MJ/litre respectively. This analysis reflects the impact of wasteful water use practices because of flood irrigation. The net energy value remains only marginally positive with increasing irrigation inputs. The net energy surplus would improve where energy efficient irrigation practices can be internalized (by metering of energy and use of efficient water management techniques) the scenario with sugarcane as feedstock is net energy positive.

Table 5 indicates that with an improvement in cane productivity by 25% and 50%, the net energy value for ethanol is obtained to be positive even after increase in the fertilizer use. The values of improved cane productivity taken for sensitivity analysis reflect the best practice scenario as reported in the literature and also validated by agricultural scientists working in agricultural universities in Maharashtra. The assumed values of productivity use are also constrained by soil quality and cropping practices. A black cotton soil may give high productivity as compared to red and yellow soil. It is observed that cane productivity declines with time without crop rotation and rationale use of fertilizers. Hence there is a limited scope of increasing the net energy value of ethanol by productivity gain.

6. Conclusion

Farm to factory net energy analysis of ethanol done using the primary data collected by interviewing farmers and data collection from the field is reported for the sugarcane growing belt in Maharashtra region of India. Principal finding of this study is that ethanol from sugarcane as a feedstock gives positive net energy value in the surveyed area. However the surplus energy is only 40%, which shows considerable scope for improvement by optimizing farming practices. The key drivers of energy input values are farming inputs and agricultural practices which are influenced by the extension services which are delivered to farmers. About 9 MJ of fossil energy is used for pumping the water for irrigating the sugarcane fields. This is more than 56% of the total fossil energy input that goes into ethanol production. The net energy value of ethanol in Maharashtra is much less than the Brazilian ethanol primarily because of differences in energy input that goes in sugarcane production. While the energy for irrigation is negligible, fertilizer consumption also is much lower than that reported for Indian scenario in the present study. The energy for irrigation in Brazilian case study is negligible since the crop in Brazil is rain fed. The net energy value of Brazilian ethanol is therefore extremely favourable compared to Indian ethanol. Shift in sugarcane cultivation to regions with favourable rainfall and use of energy efficient water use practices can bring the fossil fuel energy input for irrigation closer to Brazilian sugarcane. Net Energy Value of Indian Ethanol reduces from 6 MJ/litre to 1.5 MJ/litre if irrigation energy is increased by 50%. Gain in net energy value is negligible even with increase in cane productivity by 50% due to additional fertilizer application. Optimizing water and fertilizer use is recommended to improve net energy value of ethanol obtained from sugarcane growing belt in Maharastra.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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