Energy assessment of second generation (2G) ethanol production from wheat straw in Indian scenario

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Abstract

Impact of second-generation ethanol (2G) use in transportation sector mainly depends upon energy efficiency of entire production process. The objective of present study was to determine energy efficiency of a potential lignocellulosic feedstock; wheat straw and its conversion into cellulosic ethanol in Indian scenario. Energy efficiency was determined by calculating Net energy ratio (NER), i.e. ratio of output energy obtained by ethanol and input energy used in ethanol production. Energy consumption and generation at each step is calculated briefly (11,837.35 MJ/ha during Indian dwarf irrigated variety of wheat crop production and 7.1148 MJ/kg straw during ethanol production stage). Total energy consumption is calculated as 8.2988 MJ/kg straw whereas energy generation from ethanol is 15.082 MJ/kg straw; resulting into NER > 1. Major portion of agricultural energy input is contributed by diesel and fertilisers whereas refining process of wheat straw feedstock to ethanol and by-products require mainly in the form of steam and electricity. On an average, 1671.8 kg water free ethanol, 930 kg lignin rich biomass (for combustion), and 561 kg C5-molasses (for fodder) per hectare are produced. Findings of this study, net energy ratio (1.81) and figure of merit (14.8028 MJ/nit kg carbon) proves wheat straw as highest energy efficient lignocellulosic feedstock for the country.

Keywords 2G ethanol · Agricultural residues · Energy analysis · Lignocellulosic feedstock · Wheat straw

Introduction

India's primary energy consumption share is 5.3% of global, third biggest after China and USA in the year 2015 (2016a, b). In 2013, total primary energy consumption from coal (54.5%), crude oil (29.5%), natural gas (7.7%), hydro electricity (5.0%), nuclear energy (1.3%), wind power, solar power and biomass electricity was 595 Mtoe, excluding traditional biomass use (2015a). Energy consumption of India in different sectors for last 10 years has been presented in Fig. 1. From the figure, it is seen visibly that energy demand is increasing every year in all sectors. India's net imports were nearly 144.3 million tonnes of crude oil, 95 Mtoe coal and 16 Mtoe of liquefied natural gas which is equal to 42.9% of total primary energy consumption in 2013. Fossil fuels contribute to 70% of India's electricity generation. Country's

dependence on energy imports is expected to exceed 53% of the total consumption. Around 31% of total Indian imports are oil imports (YEP 2011). Therefore, to meet the energy demand, country will have to import huge amounts of energy from other countries.

Currently, India is fourth highest green house gas (GHG) emitter (Chandrakant 2015). Various technologies in the field of renewable energy have been developed for heat and electricity generation such as biomass combustion, hydro power and wind mills. But in the transportation sector, which is ever-growing, no similar kind of developments for alternative energy sources production has happened (Bentzen et al. 2006). Hence, India needs to find other sustainable and renewable energy generation sources to meet its demand, providing a good market for biofuels. Sourcewise installed capacities of various renewable powers of last 2 years is shown in Fig. 2. Wind power source contributes highest, whereas waste to energy source or biofuel based energy source is still in its initial stage (biofuel production accounts only 1% of global production) (Chandrakant 2015).

Commercially only bioethanol and biodiesel are produced in India (Chandrakant 2015). Presently, first generation

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Fig. 1 Trend of categorywise energy consumption from 2005-06 to 2014-15 (2015b)

Fig. 2 Sourcewise installed capacities of renewable powers in India as on 31.03.2013 and 31.03.2014 (2015c)

feedstocks (sugarcane, maize, sugarbeet and cassava) are commonly used for bioethanol production which competes with food crops, questioning food security and sustainability issues. Thus, there is tremendous potential for second generation agricultural residues based bioethanol (2G ethanol) in India, reducing GHG emissions and competition with food consumption (Chandrakant 2015). Government of India has set a mandate of 5% blending of renewable biofuel in both petrol and diesel. Currently, diesel biofuel blending is near zero and petrol blending is around 3% from molasses based ethanol. Annual requirement of ethanol stands at about 500 crore litre in India but total installed capacity is just about 265 crore litre. Therefore, targets of 10% blending by 2017 and 20% by 2020 which is set by biofuel policy of India look too far unless 2G ethanol production technologies are successfully demonstrated at commercial level (2016c). Proposed government initiative to meet these requirements

are as follows: a. Domestic off-take guarantee (2G ethanol blend mandate enforced) b. Facilitate feedstock security c. De-risking incentives for first few plants to encourage local company participation and d. Conducive climate/tools to attract investors. These policies impact directly and arise potential opportunities which include; (1) ~ 2 million tonnes 2G ethanol (2) ~ \$5 billion investment for 20 plants. (3) ~ 15,000 good jobs (7400 high-value) (4) Additional annual income ~ \$5 billion (5) Off-set oil import (balance of payments) and (6) Rural development by 2020 (2015d).

For qualification as a viable fossil fuel substitute, an alternative fuel should have superior economic and environmental benefits and must have net energy gains over energy sources required to produce it (Hill et al. 2006). Alternative fuel should have a potential of offsetting extraction and burning cost of fossil fuels. Net energy benefit of fossil fuel replacement should be estimated by calculating net energy contained in the biomass as well as energy required in feedstock growing and converting it into ethanol (Bansal et al. 2016). Net Energy ratio (NER) is the most widely used tool for determination of energy efficiency of ethanol production. It can be defined as the ratio of output energy obtained from ethanol and energy consumed to produce it (Schmer et al. 2008). Some of the previous studies have shown net energy gain from producing ethanol from cellulosic feedstock such as switch grass as much as 343% (McLaughlin and Walsh 1998). In one of the important recent studies, Energy and resource group biofuel analysis meta model (EBAMM) was used and approximate 23 MJ/L of ethanol energy gain was reported in cellulosic ethanol production (Ferrell 2009); similar range has been reported by Schmer et al. (2008). They have done their studies on ten switch grass farms established on marginal lands ranging from 3 to 9 ha with net energy of

21.5 MJ/L of ethanol. Swana et al. (2011) compared the energy yield of 2G ethanol and corn-derived bioethanol using Life cycle assessment (LCA). They found significantly higher energy gain in cellulosic ethanol (15.9 MJ/L) than corn-based ethanol. Net energy value (NEV) of cellulosic feedstocks like switch grass (8.80 MJ/L of ethanol) and *Miscanthus* (11.99 MJ/L of ethanol) were determined (Bansal et al. 2016). However, few studies (Pimental and Petzek 2005; Pimental 2003) have reported a negative net energy for ethanol production from grain crops as well as cellulosic feedstocks, which have further been criticized by other authors for incorrectly ignoring some important co-products and using obsolete data (Ferrel 2009). Difference in biomass yield might be the reason of variation in the net energy gains among different studies.

To improve net energy gain, several works have been done during past years on lignocellulosic ethanol to increase its productivity and reducing energy consumption in the production process. In one of the major works particularly on wheat straw, enhanced saccharification of biologically pretreated wheat straw was achieved for ethanol production resulting into an increase of sugar yield from 33 to 54% as well as reduction of the enzymatic mixture quantity by 40% (Abelairas et al. 2013a). Cellulose (34–40%), hemicellulose (30–35%) and lignin (14–15%) are the major components of wheat straw (Liu et al. 2005; Lawther et al. 1996 and Sun et al. 1998). In another study, fermentation of biologically pretreated wheat straw was done where highest overall ethanol yield was obtained with the yeast *Pachysolen tannophilus* which yielded 163 mg ethanol per gramme of raw wheat straw (Abelairas et al. 2013b). During study on Lignin and silica generated from black liquor during the production of bioethanol from rice straw, Sulphuric acid was concluded the best reagent, economically more suitable and two step treatment is found more efficient in providing a superior product in quality (Minu et al. 2012). During study on exergy analysis of ethanol production from lignocellulosic biomass, highest exergy efficiency (Steam Explosion Pretreatment + SSF + Dehydration) reaching 79.58% was achieved (Velmurugan and Muthukumar 2012). Furthermore, *Lantana camara* was used for bioethanol production; 87.2% lignin removal and 80.0% saccharification were achieved with 17.7 g/L ethanol production and corresponding yields of 0.48 g/g using *Saccharomyces cerevisiae* (Kuhad et al. 2010). Sono-assisted enzymatic saccharification of sugarcane bagasse was done for bioethanol production where maximum glucose yield obtained was 91.28% of the theoretical yield and maximum amount obtained was 38.4 g/L (Ojeda et al. 2011). The application of low-intensity ultrasound enhanced the enzyme release and intensified the enzyme-catalysed reaction in this study. Readers are advised to refer an overview article by Baeyens et al. (2015) to understand the current

challenges and opportunities in improving the bioethanol production.

Wheat straw is a byproduct from wheat crop; therefore amount of straw produced is directly related to the main crop production. India covers around 13.2% of total wheat production and second largest producer after China (FAOSTAT 2012). Total area used for the wheat crop is about 30.5 million hectare in the country. Productivity of wheat has been increased up to 3145 kg/hectare in 2013 (2015e). Major productivity is reported from Haryana, Rajasthan, Uttar Pradesh and Punjab states (2015f). Crop residue burning is a common feature in UP, Punjab, Rajasthan and Haryana states of India, as they have two growing seasons usually (May–September and November–April). Therefore, farmers often set fire to the standing straw to clear the field of crop residue and want to prepare the fields for sowing another crop (Bhatnagar 2016). Although wheat straw is just a by-product from the wheat and an important cattle fodder, besides fodder and other uses, states have set some policies for straw that would promote R&D for production of cellulosic ethanol. For example, Punjab state has set up policies for management and utilisation of straw in 2013 which aims for ultimate utilisation of 1.5 million tonnes of straw per annum by 2027 (assuming 45 such plants shall be established, each consuming 30,000–35,000 tonnes of straw per annum) to produce 0.37 million kilo litre of ethanol for use as blend in fuel (based on 10% blending in current requirement of petroleum products in the state) (2013).

Biomass yield of wheat is highly sensitive to energy input, climatic zone (temperature and rainfall) and production technology level and thus could vary region to region significantly. Also, biomass losses during harvest and storage result in increased input used to produce per unit of ethanol (Emery et al. 2014). Straw-based commercial 2G ethanol costs ₹28–34/L (Sheth 2016) which is very less comparable to present price of gasoline (₹68.7/L) and petrol (₹65–78/L). However, most of the agricultural residues and straw not used in human food and as animal feed are burned on the agricultural land (Bhatnagar 2016; Mukerjee 2016).

Since energy input and yield vary with each system, it influences the NER. This study is conducted to estimate the NER of ethanol production using wheat straw in India as wheat is highly grown cereal crop here and wheat straw is largely unused (Chaba 2015). Therefore, present study has been done to explore whether it is reasonable to produce fuel ethanol from 1 ha of agricultural land used for wheat straw in India from an energy point of view, based on recent technologies for bioethanol production and average agricultural productions. All the factors for ecological sustainability and supply security are included.

Methodology and data sources

Calculation data for this study are collected from literature, various agricultural extension services, ministry of agriculture (India) and from energy statistics (India). Basis is agricultural production of irrigated dwarf variety of wheat (timely sown) under Indian conditions using standard agricultural practices since these are high-yielding varieties grown under different agroclimatic conditions laid down by the All-India coordinated wheat improvement project (2015g). Traditional manner of farming is considered using commercial pesticides and fertilisers available within the government rules and regulations imposed on agriculture sector. Technology used for ethanol production is considered as an average and data are believed to be valid in a time scale of 0–10 years from present Indian scenario. Field output (wheat straw only) is considered as sugar source in the study. By-product such as distillers dried grain with solubles (DDGS) is neglected as it is basically produced from wheat grain whereas C5-molasses are considered to be recycled to feed for animals in the agricultural business. Biomass generated is incinerated for generation of energy. CO₂ utilisation is not dealt with in this study. Due to location, area, capacity, technology involved and purpose differences, production systems and settings vary a lot. Considering an Indian scenario, main processes involved in analyses of energy generation and consumption during bioethanol production from wheat straw has been explained in Fig. 3. Energy consumption in

canal irrigation and animal is considered as zero. These variations are acknowledged and production system parameters are attempted to express by a reasonable range.

Results and discussion

Agricultural energy input

All the input data are based on 10 tonnes of farm yard manure (FYM).

Seeds

To produce any cereal crop, seeds are needed. For Indian wheat, target number of germinated seedlings depends on time of seeding. In this study, seed input range of 100 kg/ha is chosen. Energy consumption is based on estimation of previous studies (Table 1). Total energy consumed in the seed production and handling is calculated as 300 MJ/ha using Eq. (1): (Bentsen et al. 2006)

$$EC_{\text{seed}} = R_{\text{seed}} \times SE_{\text{seed}} \quad (1)$$

where EC_{seed} = Total energy consumption for the production and handling of seed R_{seed} = Seed input range and SE_{seed} = Energy consumption related to seed distribution.

Fig. 3 Main processes involved in analysis of energy generation and consumption during bioethanol production from wheat straw in Indian scenario

Table 1 Input data used for calculation of energy consumption during wheat production in the present study

Abbreviation	Input	References	Abbreviation	Specific energy input	References
R_{seed}	100 kg/ha	(2015g)	SE_{seed}	2.5–3.5 MJ/kg	(Bentsen et al. 2006); (Kuesters and Lammel 1999); (Rosenberger et al. 2001)
R_{herb}	1.4 kg/ha	(2015g)	SE_{herb}	173.5 MJ/kg	(Singh et al. 2007)
R_{pest}	0.48 kg/ha	(2015g)	SE_{pest}	40.3–580 MJ/kg	(Bentsen et al. 2006)
Fertilizers and manures					
Abbreviation	Inputs	Input range	Specific energy input	Energy consumption (MJ/ha) = (column 1 $\times$ column 2)	References
EC_{manure}	Energy consumption in manure handling and application	10 T/ha	42.21 MJ/T	422.1	(Bentsen et al. 2006)
$EC_{\text{N-com}}$	Energy consumption in commercial N-fertiliser proportion application	60 kg/ha	38–76.7 MJ/kg	3441	(Börjesson 1996; Dalgaard et al. 2004; Dalgaard et al. 2001; Feldvoss et al. 2002; Refsgaard et al. 1998; Rosenberger et al. 2001)
$EC_{\text{P-com}}$	Energy consumption in commercial P-fertiliser proportion application	25 kg/ha	6.8–33 MJ/kg	497.5	(Dalgaard et al. 2004; Dalgaard et al. 2001; Feldvoss et al. 2002; Refsgaard et al. 1998; Rosenberger et al. 2001)
$EC_{\text{K-Com}}$	Energy consumption in commercial K-fertiliser proportion application	0	0	0	(Dalgaard et al. 2004; Dalgaard et al. 2001; Feldvoss et al. 2002; Refsgaard et al. 1998; Rosenberger et al. 2001)

Agricultural chemical inputs

Production of Indian wheat is highly dependent upon nitrogen, phosphorus and potassium manures. These levels are highly variable which depend on soil, crop and previously grown crop.

Fertilisers The allowable input range of nutrients to agricultural crops is defined by norms of Indian agricultural ministry. For irrigated dwarf variety of wheat, the nitrogen norm is 110 kg/ha. More than 50% of this amount comes from application of 10–15 tonne/hectare FYM. Nutritional requirements of some of the important wheat varieties are shown below in Table 2.

Manures Manures are the primary nitrogen supplier of wheat crop and act as a supplement to commercial nitrogen fertilisers. Here, FYM is considered as nitrogen supplier which varies in all manures. It is assumed that manure is applied directly to the soil in slurry from animals. Nutritional com-

position of FYM is presented in Table 3. Remaining amount comes from commercial fertilisers. The direct energy consumption by handling and applying manures (FYM) amounts to 42.21 MJ/T (Table 1). Energy consumptions in commercial N- and P-fertilisers are 57.35 and 19.9 MJ/kg, respectively. FYM are sufficient to fulfil potassium requirement of crop. Calculation data for energy consumption in fertilisers and manure use are presented in Table 1,

where R_{herb} = Herbicides input range R_{pest} = Pesticides input range SE_{herb} = Energy consumption related to herbicides production and SE_{pest} = Energy consumption related to pesticides production.

Herbicides In conventional farming, herbicides are used to control broad leaf weeds in wheat crop. It is used at a very low dosage of 1.4 kg/ha. Herbicide should be safe to the animals, farm workers and main crop. Input data for calculation of energy consumption in herbicides use are presented in Table 1.

Table 2 Varieties of Indian wheat crop and their nutritional requirements (2015g)

Varieties	N (kg/ha)	P ₂ O ₅ (kg/ha)	K ₂ O (kg/ha)
Irrigated Deshi and Dwarf varieties (late sown)	70	40	40
Irrigated dwarf varieties (timely sown)	110	50	40
Un-Irrigated/rainfed Deshi varieties	25	20	15
Un-Irrigated/rainfed Dwarf varieties	50	30	20

Table 3 Nutritional composition of FYM (Srikanth 2016)

Nutrients	Input (%)	Nutritional composition of FYM (kg/ha)
N	0.5	50–75
P	0.25	25–375
K	0.4	40–60
Ca	0.08	8–12
S	0.02	2–3
Zn	0.004	0.4–0.6
Cu	0.0003	0.03–0.045
Mn	0.007	0.7
Fe	0.45	45–67.5

Total energy consumption of herbicide application in wheat crop is calculated as 242.9 MJ/ha from Eq. (2).

$$EC_{\text{herb}} = R_{\text{herb}} \times SE_{\text{herb}}, \quad (2)$$

(Bentsen et al. 2006) where EC_{herb} = Total energy consumption associated with herbicides application.

Pesticides Pesticides are applied to protect the crop against damage caused by insects and fungus. The application rate is 0.3–0.66 kg/ha. The crop-specific target for irrigated dwarf variety of wheat is 0.48 kg/ha. Energy consumption for pesticide production varies a lot between different references. In this study, data used for calculation of energy consumption in pesticides application are presented in Table 1.

Diesel

Any agricultural machine needs diesel oil and lubricants to run. Net calorific value and density of diesel is 42.7 MJ/kg and 0.83 kg/L, respectively, which gives a direct energy input of 35.44 MJ/L of diesel consumed to the agriculture.

Energy consumption for the manufacturing and distribution of diesel oil varies in different studies. Based on study by Singh et al. (2007), calculated mean energy consumption associated with diesel was found to be 3749.68 MJ/ha of three major wheat producing Indian states (Uttar Pradesh, Rajasthan and Punjab).

Human

It varies from region to region of country. Energy consumed by labour can be calculated using the following equation:

$$\text{Energy consumed by labor} = \frac{\text{work hours per man} \left(\frac{h}{ha} \right) \times \text{Energy consumed per person (MJ)}}{\text{Area worked (ha)}}. \quad (3)$$

However, in this study, 738.04 MJ/ha (calculated mean human consumption of Punjab, Uttar Pradesh and Rajasthan states) of human energy consumption is considered (Singh et al. 2007).

Machinery

Machines and tools (tractors, harvesters and ploughs) are basically used in agricultural sector. Manufacturing of machines require steel and other metals along with some other materials to be produced and ore extraction is also needed. All these operations consume energy. Usually, energy embodied in machinery is calculated by using economic input–output life cycle assessment (EIO-LCA) model of Carnegie Mellon University (CMU) (Bansal et al. 2016). However, for the present study, mean energy consumption has been calculated (390.05 MJ/ha) from study done by Singh et al. (2007) for machine manufacturing.

Electricity

Agricultural sector consumes electricity for heat, light, ventilation and various other purposes.. Energy carriers also need to be converted into transmission loss and electricity. This step also requires energy along with the direct use. Calculated mean energy consumption in electricity is taken as 1907.21 MJ/ha based on the study by Singh et al. (2007)

Therefore, Net agricultural energy consumption in timely sown irrigated Indian dwarf variety of wheat production is calculated as 11,837.35 MJ/ha.

$$EC_{\text{AGRI}} = EC_{\text{SEED}} + EC_{\text{MAN}} + E_{\text{CN-COM}} + E_{\text{CP-COM}} + EC_{\text{Herb}} + EC_{\text{Pest}} + EC_{\text{Diesel}} + EC_{\text{Human}} + EC_{\text{Mac}} + EC_{\text{Elec}}, \quad (4)$$

where EC_{AGRI} = Total energy consumption during straw production and handling, EC_{Pest} = Total energy consumption associated with pesticides application, EC_{Diesel} = Total energy input in diesel oil consumption, EC_{Human} = Total energy consumption by labour during straw production and handling, EC_{Mac} = Energy consumption in agricultural machine manufacture and EC_{Elec} = Electricity input in Agriculture.

Some of the energy inputs vary significantly in the above-mentioned states; therefore, sensitivity analysis has been conducted to analyse its effect on net agricultural energy consumption (Fig. 4).

Energy inputs into ethanol production

Steam and electricity

Steam and electricity requirements for the conversion of wheat grain to ethanol and by products are estimated to 3.6 GJ per tonne and 100 KW per tonne of grain, respectively. Processing of straw into ethanol require 3.8 GJ steam and 220 KW electricity per tonne of wheat straw (Bentsen et al. 2006).

Electricity Existing infrastructure can be used to draw electricity. In this study, it is assumed that major portion of electricity is generated from fossil fuels and some amount from renewable energies. According to the previous studies 2.605 MJ of electricity is required per kg of straw. Transmission and distribution grid loss in India is (6–8%) in 2015 and depends on grid balancing, import, export and capacity adjustments (Aniti 2015).

Steam In this study, it is assumed that low-cost surplus steam is available at the appropriate pressure and temperature level. It is the case of integrated biorefinery with large power plants where enormous quantity of energy is removed as a waste stream. In large-scale condensing power plants, steam is expanded using turbine results into electric energy

production which lead to enthalpy loss in the steam from expansion. This loss can be recovered largely and further converted to process steam for biorefinery with minimal fuel addition. Based on the previous studies, it is found that 4.332 MJ of steam is needed per kg of straw for fuel ethanol production (Bentsen et al. 2006).

Chemicals

A wide range of chemicals are used during different steps of production process. Some of the important chemicals are listed in Table 4. It is assumed that same chemicals with same quantities are required in conversion of both grain and straw into ethanol.

In the present study, calculated mean energy consumption for the chemicals used in ethanol production is taken as 0.4385 MJ/kg ethanol or 0.122 MJ/kg straw.

Machinery

Machines and equipments (bioreactors, reactor for hydrolysis, distillation, etc.) are basically used in ethanol production plants. As stated above, manufacturing of machines requires steel and other metals along with some other materials to be

Fig. 4 Sensitivity analysis for **a** Diesel. **b** Human. **c** Machinery. **d** Electricity consumption in agricultural energy input

Table 4 Energy requirement of some common chemicals used during bioethanol production

Chemical	Quantity (Elsam 2005) (kg/tonne ethanol)	Energy consumption		References
		(MJ/kg chemical)	(MJ/tonne ethanol)	
Amylase	1.2	6.32	7.58	(Bernesson 2004; Bernesson et al. 2004)
Protease	1.1	6.32	6.95	(Bernesson 2004; Bernesson et al. 2004)
Sulphuric acid	25	3	75	(Bernesson 2004; Bernesson et al. 2004)
Calcium chloride	1.2	1.55	1.86	(Bernesson 2004; Bernesson et al. 2004)
Urea	5.8	6.2	35.96	(Bentsen et al. 2006)
Phosphorus acid	5.8	20	116	(Bernesson 2004; Bernesson et al. 2004)
NaOH	3.6	10.4–49.2	37.44–177.12	(Bernesson et al. 2004); Bentsen et al. 2006
Ammonia water	12	5.2	62.4	(Bentsen et al. 2006)
Water	2000	0.005	10	(Feldvoss et al. 2002)
Sum			369–508	

produced and ore extraction is also needed. All these operations consume energy. Calculated mean energy consumption data for machine manufacturing are taken as 0.2 MJ/kg ethanol or 0.0558 MJ/kg straw (Singh et al. 2007).

Therefore, total energy input in ethanol production from wheat straw is calculated as 8.2988 MJ/kg wheat straw using the following equation:

$$EC_{TOTAL} = EC_{AGRI} + EC_{STEAM} + EC_{ELECTRICITY} + EC_{CHEMICALS} + EC_{MACHINERY}, \quad (5)$$

where EC_{TOTAL} = Total Energy consumption during ethanol production, EC_{STEAM} = Total Energy input related to steam consumption during ethanol production, $EC_{ELECTRICITY}$ = Total Energy input related to electricity consumption during ethanol production, $EC_{CHEMICALS}$ = Total Energy input related to chemicals during ethanol production and $EC_{MACHINERY}$ = Total Energy input related to machinery use during ethanol production.

Agricultural outputs from wheat agricultural production are estimated on the basis of national statistics for year 2014. These data are based on the total production of irrigated dwarf wheat in India and cover all intensities, soil types, production technologies and agricultural practices. Mean annual yield of winter wheat in India is taken as 4000 kg/ha. For the same year, mean annual yield of straw from Indian wheat is 6000 kg/ha as ratio of wheat grain: wheat straw was found to be around 1:1.5 from various studies (2014). Therefore, proportional yield of wheat straw = $6000/(4000 + 6000) = 0.6$ and total agricultural energy input for production of Wheat straw is calculated as 7102.41 MJ/ha or 1.184 MJ/kg straw.

Energy output during ethanol production and by-products

During the refinement of wheat straw into ethanol, ligno-cellulosic biomass runs through a series of processes like liquifaction, saccharification, fermentation, distillation and drying. Outputs from the conversion process of wheat straw into ethanol are water free ethanol (~ 99%), C5-molasses, biomass and pure CO₂.

Ethanol

The estimated ethanol output from wheat straw is based on conventional technology. The output of ethanol from straw is based on the assumption that both pentose and hexose sugars are cofermented. On an average, output from 1 ha of wheat land can produce 1671.8 kg water free ethanol. Fuel ethanol (blend or pure) has many possible end uses. In this study, no specific application of the ethanol is considered. Energy output from ethanol during ethanol production has been calculated and shown in Table 5.

C5-molasses

13.4% of wheat straw input can be extracted as C5-molasses (561 kg/ha) (Bentsen et al. 2006). It contains large amounts of organic acids which is well suited as fodder (substitute of DDGS). Total energy output from C5-molasses during ethanol production has been shown in Table 5.

Table 5 Energy output during ethanol production and by-products

Abbreviation	Input	Input Range (kg/kg straw)	Abbreviation	Specific Energy input range (MJ/kg)	Total energy produced (MJ/kg straw)	References
P _{EtOH}	Ethanol produced	0.274	EC _{EtOH}	26.7	7.319	Present study
P _{biomass}	Biomass Produced	0.40	EC _{biomass}	17.5	7.0	(Elsam 2005)
C5-molasses	C5-molasses produced	0.134	EC _{C5-molasses}	5.7	0.7638	(Bentsen et al. 2006)

Biomass

After hydrolysis, remaining solid residue of lignocellulosic biomass contains only lignin portion as cellulose and hemicellulose breakdown into its monomeric sugars. It has an estimated lower heating value (LHV) of 17.5 MJ/kg. The residual biomass can thus be used internally as fuel. Total energy output from biomass during ethanol production has been shown in Table 5.

CO₂

CO₂ can be considered as a major by-product from ethanol production plant. The area based output is estimated as 2897 kg/ha (Bentsen et al. 2006). Pure CO₂ is used in beer and soft drink production. It can also be used as carbon source in chemical industries. It does not have any effect on the carbon balance if emitted. Therefore, energy output calculation based on CO₂ is not included in the study.

Therefore, total energy output during ethanol production from wheat straw is 15.082 MJ/kg straw using Eq. (6):

$$EC_{\text{OUTPUT}} = EC_{\text{EtOH}} + EC_{\text{biomass}} + EC_{\text{C5-molasses}}, \quad (6)$$

where EC_{OUTPUT} = Total energy generated during ethanol production, EC_{EtOH} = Total energy generated from ethanol, EC_{biomass} = Total energy generated from biomass produced and $EC_{\text{C5-molasses}}$ = Total energy generated from C5-molasses.

Therefore, energy efficiency or NER of fuel ethanol from wheat straw is calculated as 1.81 (Total energy input/total energy output).

Carbon emissions and uptake

Analyses on wheat straw, a lignocellulosic feedstock as a renewable energy source conclude that it offers great potential to reduce greenhouse gases through fossil fuels' replacement. On the basis of life cycle, it has been found that CO₂ emissions from these biomasses do not increase the overall burden of carbon to the atmosphere. Greenhouse gas emissions can be reduced by both carbon sequestration and bioenergy production (Prakash et al. 1998). Biofuel use instead of fossil fuel has the potential to reduce global

warming to greater extent than when it is used for carbon sequestration.

During the bioethanol production process, significant amount of carbon emissions takes place in the form of CO₂. In burning of straw and biogas in the boilers, some amount of CO₂ releases while major amount releases during fermentation (Prakash et al. 1998). During ethanol transportation and its eventual combustion also, CO₂ would also be released. However, in all the processes except transportation, raw material used and energy inputs are derived from biomass collected from nearby fields. Therefore, it can be assumed that major amount of carbon, which is released, is absorbed through photosynthesis eventually which results negligible gross carbon emissions.

Figure of merit for bioethanol

Figure of merit for a fuel

$$= \frac{\text{Net energy yield from 1 kg fuel (MJ)}}{\text{Gross CO}_2\text{emission from 1 kg fuel (kg)}} \quad (7)$$

(Prakash et al.1998).

Figure of merit represents quality of any fuel. Higher value claims better fuel. It provides more rational choice of rather than choosing the fuel purely on economic grounds. Apart from CO₂, other polluting agents such as SO_x, NO_x, aldehydes and lead emission may also be considered (Prakash et al. 1998). However, in this study, CO₂ emission is only considered as it is the main contributor for global warming. Here figure of merit is of bioethanol produced in Indian conditions calculated using wheat straw. As net energy available of bioethanol calculated above is 14.8028 MJ/kg wheat straw and gross carbon emissions are negligible, figure of merit for bioethanol is evaluated as 14.8028 MJ/zero kg carbon.

Comparison with figures of merit of fossil fuels

Detailed energy consumption during fuel production is required to assess accurate figure of merit of any fuel. Figure of merit of some of the fossil fuels is obtained from

Table 6 Fuels comparison (modified from Prakash et al. 1998)

Fuels	Energy yield ratio (G/F)	Gross C emission (kJ/GJ gross output)	N/G value	Calorific value (energy content)	Specific energy content (MJ/kg)	Gross carbon emission (kJ/kg of fuel)	Net Energy (MJ/kg of fuel)	Figure of merit
Natural gas	23.2	13.5	0.96	37.3 MJ/m ³	63.7	0.86	61.2	61.2 MJ/0.86 kg C
Coal	8.6	24.6	0.90	29.3 GJ/tonne	29.3	0.72	25.8	25.8 MJ/0.72 kg C
Oil	10.0	19.9	0.88	44.8 GJ/tonne	44.8	0.89	40.3	40.8 MJ/0.89 kg C
Bioethanol						Negligible	14.8028	14.8028 MJ/nil kg C

available data and presented in Table 6. Symbol G denotes gross energy which is produced by the fuel on combustion. F indicates total input energy consumed during fuel production process.

$$\frac{\text{Net energy}(N)}{\text{Gross energy}(G)} = 1 - \frac{1}{\left(\frac{G}{F}\right)} \quad (\text{Prakash et al. 1998}) \quad (8)$$

Rearranging Eq. (7) gives

$$F = G - N \quad (9)$$

(Prakash et al. 1998)

Net energy of any fuel can be obtained by multiplying its N/G ratio with calorific value (net energy content). Calorific value of fossil fuels ratios are shown below in Table 6.

Gross carbon emission which is shown in Table 6 can be used to calculate its amount in kg/kg of a fuel by taking its calorific value into account. Calculated net energy, kg gross carbon emission/kg of fuel and figure of merit are presented below in Table 6 for fossil fuels along with bioethanol.

Conclusion and future prospective

India is a developing country and its industry is continuously increasing; hence, the energy demand will also be increasing gradually. Although India has a high usage and potential of renewables, still fossil fuels are used substantially, causing environmental pollution and threatens sustainability. India has signed the Kyoto Protocol with some eligibility, but still needs to reduce GHG emissions and propose to use renewables in transportation, industry and agriculture. India imports high cost energy for transportation, electricity generation and heating from other countries every year and already consumed most of its consumed proved reserves. Bioethanol, an alternative fuel to gasoline is clean, domestic and renewable, having similar properties to gasoline and also supports national and global sustainability. Presently, food crops are used in the ongoing first generation bioethanol production, which needs to be shifted towards second generation (from

lignocellulosic biomass) to avoid food vs. fuel conflict. Considering India's biomass potential and its dependence on foreign energy sources, 2G ethanol productions and its utilisation become prominent.

NER and carbon balance are two important factors to be considered when studying the impact of lignocellulosic feedstocks to the environment. An alternative to fossil fuel must have lesser negative impact on environment. $NER > 1$ is an indicator of net energy gain in the whole production process, showing that energy output is greater than energy input, whereas $NER < 1$ implies unsustainability of a production process.

To contribute in the pool of existing knowledge, this study has been conducted and shows that anhydrous ethanol production from wheat straw in Indian scenario has positive energy benefits and it can be successfully used as a fuel under Indian conditions. NER for a conventional production process in current practice is calculated about 1.8 and figure of merit for is obtained as 14.8 MJ/nil kg carbon. Major portion of input energy is contributed by diesel and fertilizers. Figure of merit values comparison show that choice of an alternative appropriate fuel in the Indian economy would be dominated by their energy ratios and figures of merit. Our analysis included energy required to produce machinery, farm equipment, human labour and other related capital factors which have been omitted in some related studies.

Additionally, considering the social and economic structure of India, most of the agricultural residues not used in human food and as animal feed are burned on the agricultural land. Therefore, examining climatic conditions and soil structure of the country, instead of this traditional burning method of energy conversion and waste elimination, bioethanol production from these feedstocks will provide a great socioeconomic gain. Considering all these aspects, India should improve wheat straw-based second generation bioethanol, increase its number of facilities and implement more policies. Research and development studies on exploration of lignocellulosic feedstocks should be improved to decrease the total production cost.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflicts of interest.

References

- (2016a) India's energy market in 2015. BP Statistical Review 2016. <https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf>. Accessed 27 Dec 2017
- (2016b) World Energy Consumption by Country 2016. <http://www.usdebtclock.org/>. Accessed 17 June 2017
- (2016c) India gets its first 2G ethanol plant in Uttarakhand. The Economic Times—Agriculture. <http://economictimes.indiatimes.com/news/economy/agriculture/india-gets-its-first-2g-ethanol-plant-in-uttarakhand/articleshow/51948347.cms>. Accessed 28 Dec 2017
- (2015a) BP Statistical Review of world energy June 2015. <https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-full-report.pdf>. Accessed 28 Dec 2017
- (2015b) Growth of Electricity Sector in India From 1947 to 2015. Central Electricity Authority, Ministry of Power, Government of India. http://www.cea.nic.in/reports/others/planning/pdm/growth_2015.pdf. Accessed 28 Dec 2017
- (2015c) Energy statistics. Central statistics office, Ministry of statistics and programme implementation, Government of India, New Delhi. http://www.mospi.nic.in/sites/default/files/publication_reports/Energy_Statistics_2015r.pdf. Accessed 9 July 2017
- (2015d) Cellulosic ethanol emerging opportunities in India. Novozymes http://2015.re-invest.in/presentations/03_New_Emerging_Technologies/Melssen.pdf. Accessed 28 Dec 2017
- (2015e) Annual Report. Department of Agriculture, Cooperation & Farmer's Welfare, GOI. <http://www.agricoop.nic.in/sites/default/files/Final%20Annual%20Report%20English.pdf>. Accessed 28 Dec 2017
- (2015f) Wheat. Farmers Portal, Department of Agriculture & Cooperation and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India. <http://www.farmer.gov.in/#>. Accessed 8 June 2017
- (2015g) Wheat. IIWBR <http://nsdl.niscair.res.in/jspui/bitstream/123456789/502/1/WHEAT%20-%20formatted.pdf>. Accessed 28 Dec 2017
- (2014) Economic survey 2012-13- Agriculture. National data sharing and Accessibility policy (NDSAP), Ministry of finance, Department of economic affairs, Government of India. <https://data.gov.in/catalog/index-numbers-agricultural-production>. Accessed 10 June 2017
- (2013) Policy for Management and Utilization of Paddy Straw in Punjab 2013 <http://pscst.gov.in/files/Draft%20Policy%20for%20Management%20&%20Utilization%20of%20Paddy%20Straw.pdf>. Accessed 28 Dec 2017
- Aniti L (2015). India aims to reduce high electricity transmission and distribution system losses. Today in energy, eia, U.S. Energy Information administration <https://www.eia.gov/todayinenergy/detail.php?id=23452>. Accessed 12 Dec 2017
- Baeyens J, Kang Q, Appels L, Dewil R, Lv Y, Tan T (2015) Challenges and opportunities in improving the production of bio-ethanol. Prog Energy Combust Sci 47:60–88. <https://doi.org/10.1016/j.pecs.2014.10.003>
- Bansal A, Illukpitiya P, Tegegne F, Singh SP (2016) Energy efficiency of ethanol production from cellulosic feedstock. Renew Sustain Energy Rev 58:141–146. <https://doi.org/10.1016/j.rser.2015.12.122>
- Bentsen NS, Felby C, Ipsen KH (2006) Energy balance of 2nd generation bioethanol production in Denmark. Denmark: Dong Energy and Royal Veterinary and Agricultural University. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.464.5701&rep=rep1&type=pdf>. Accessed 28 Dec 2017
- Bernesson S (2004) Life cycle assessment of rapeseed oil, rape methyl ester and ethanol as fuels—a comparison between large- and small scale production. Dissertation, Swedish University of Agricultural Sciences, Uppsala
- Bernesson S, Nilsson D, Hansson PA (2004) A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. Biomass Bioenerg 26(6):545–559. <https://doi.org/10.1016/j.biombioe.2003.10.003>
- Bhatnagar GV (2016) High pollution levels from straw burning shows green tribune orders were neglected. The WIRE. <http://www.downtoearth.org.in/news/crop-burning-punjab-haryana-s-kill-r-fields-55960>. Accessed 28 Dec 2017
- Börjesson P (1996) Energy analysis of biomass production and transportation. Biomass Bioenerg 11(4):305–318. [https://doi.org/10.1016/0961-9534\(96\)00024-4](https://doi.org/10.1016/0961-9534(96)00024-4)
- Chaba AA (2015) Environmentally friendly: when they don't burn straw in fields. The Indian express <http://indianexpress.com/article/india/india-news-india/environmentally-friendly-when-they-dont-burn-straw-in-fields/>. Accessed 28 Dec 2017
- Chandrakant U (2015) Biofuel potential in India. Réseau Biofuelnet Canada <http://www.biofuelnet.ca/2015/04/01/biofuel-potential-india/>. Accessed 28 Dec 2017
- Dalgaard T, Halberg N and Porter JR (2001) A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agric Ecosyst Environ 87 (1): 51–65. <http://orgprints.org/15521/1/15521.pdf>. Accessed 28 Dec 2017
- Dalgaard T, Halberg N, Jørgensen MH (2004) Status for energiinput og-output i økologisk jordbrug samt muligheder for energibesparelser. In: Jørgensen U, Dalgaard T (eds) Energi i økologisk jordbrug—reduktion af fossilt energiforbrug og produktion af vedvarende energi, Forskningscenter for Økologisk Jordbrug, pp 25–45. http://orgprints.org/3043/1/rap_19.pdf. Accessed 28 Dec 2017
- Elsam (2005) Essential thinking <http://www.elsam.dk/multimedia/essentialthinkingenkeltider.pdf>. Accessed 28 Dec 2017
- Emery I, Dunn JB, Han H, Wang M (2014) Biomass storage options influence net energy and emissions of cellulosic ethanol. Bioenerg Res 8(2):590–604. <https://doi.org/10.1007/s1215>
- FAOSTAT (2012) Food and agriculture organization of the United Nations, Statistics division <http://faostat3.fao.org/wds/rest/exporter/streamexcel>. Accessed 12 Aug 2017
- Feldvoss C, Kann M, Rosing L, Leth KD, Mundt P, Pedersen H, Skovsby K and Nielsen AM (2002) Oversigt over miljøpåvirkninger fra rundstykker. <http://www.lcafood.dk/>. Accessed 16 July 2017
- Ferrel J (2009) DOE's bioenergy program. Presented at the role of extension in energy. Farm Foundation, Little Rock, AK. <https://www.farmfoundation.org/news/articlefiles/1704-Ferrell.pdf>. Accessed 28 Dec 2017

- Hill J, Nelson E, Tilman D, Polasky S and Tiffany D (2006) Environmental, economic and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc Natl Acad Sci USA*. 103 (30): 11206–11210 <http://www.pnas.org/condtent/103/30/11206.full>. Accessed 28 Dec 2017
- Kuesters J, Lammel J (1999) Investigations of the energy efficiency of the production of winter wheat and sugar beet in Europe. *Eur J Agron* 11(1):35–43. [https://doi.org/10.1016/S1161-0301\(99\)00015-5](https://doi.org/10.1016/S1161-0301(99)00015-5)
- Kuhad RC, Gupta R, Khasa YP, Singh A (2010) Bioethanol production from *Lantana camara* (red sage): pretreatment, saccharification and fermentation. *Bioresour Technol* 101:8348–8354. <https://doi.org/10.1016/j.biortech.2010.06.043>
- Lawther JM, Sun RC, Banks WB (1996) Fractional characterization of alkali-labile lignin and alkali-insoluble lignin from wheat straw. *Ind Crops Prod* 5:291–300. [https://doi.org/10.1016/S0926-6690\(96\)00028-3](https://doi.org/10.1016/S0926-6690(96)00028-3)
- Liu R, Yu H, Huang Y (2005) Structure and morphology of cellulose in wheat straw. *Cellulose* 12:25–34. <https://doi.org/10.1023/B:CELL.0000049346.28276.95>
- López-Abelairas M, Lu-Chau TA, Lema JM (2013a) Enhanced saccharification of biologically pretreated wheat straw for ethanol production. *Appl Biochem Biotechnol* 169:1147–1159. <https://doi.org/10.1007/s12010-012-0054-5>
- López-Abelairas M, Lu-Chau TA, Lema JM (2013b) Fermentation of biologically pretreated wheat straw for ethanol production: comparison of fermentative microorganisms and process configurations. *Appl Biochem Biotechnol* 170:1838–1852. <https://doi.org/10.1007/s12010-013-0318-8>
- McLaughlin SB, Walsh ME (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass Bioenerg* 14(4):317–324. [https://doi.org/10.1016/S0961-9534\(97\)10066-6](https://doi.org/10.1016/S0961-9534(97)10066-6)
- Minu K, Kurian JK, Kishore VVN (2012) Isolation and purification of lignin and silica from the black liquor generated during the production of bioethanol from rice straw. *Biomass Bioenerg* 39:210–217. <https://doi.org/10.1016/j.biombioe.2012.01.007>
- Mukerjee P (2016) Crop Burning: Punjab and Haryana's killer fields. Down to earth. <http://www.downtoearth.org.in/news/crop-burning-punjab-haryana-s-killer-fields-55960>. Accessed 28 Dec 2017
- Ojeda K, Sánchez E, Kafarov V (2011) Sustainable ethanol production from lignocellulosic biomass-application of exergy analysis. *Energy* 36:2119–2128. <https://doi.org/10.1016/j.energy.2010.08.017>
- Pimental D (2003) Ethanol fuels: energy balance, economics and environmental impacts are negative. *Nat Resour Res* 12(2):127–134. <https://doi.org/10.1023/A:1024214812527>
- Pimental D, Patzek TW (2005) Ethanol production using corn, switch grass and wood; biodiesel production using soybean and sunflower. *Nat Resour Res* 14(1):65–76. <https://doi.org/10.1007/s11053-005-4679-8>
- Prakash R, Henham A, Bhat IK (1998) Net energy and gross pollution from bioethanol production in India. *Fuel* 77(14):1629–1633. [https://doi.org/10.1016/S0016-2361\(98\)00085-4](https://doi.org/10.1016/S0016-2361(98)00085-4)
- Refsgaard K, Halberg N, Kristensen ES (1998) Energy utilization in crop and dairy production in organic and conventional livestock production systems. *Agric Syst* 57(4):599–630. [https://doi.org/10.1016/S0308-521X\(98\)00004-3](https://doi.org/10.1016/S0308-521X(98)00004-3)
- Rosenberger A, Kaul HP, Senn T, Aufhammer W (2001) Improving the energy balance of bioethanol production from winter cereals: the effect of crop production intensity. *Appl Energy* 68(1):51–67. [https://doi.org/10.1016/S0306-2619\(00\)00036-2](https://doi.org/10.1016/S0306-2619(00)00036-2)
- Schmer MR, Vogel KP, Mitchell RB and Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. *Proc Natl Acad Sci USA*. 105 (2): 464–9. <http://www.pnas.org/cgi/content/full/0704767105/DC1>
- Sheth A (2016) Biomass to bioethanol- second generation technology by praj <https://www.aidaindia.org/pdf/2.pdf>. Accessed 28 Dec 2017
- Singh H, Singh AK, Kushwaha H, Singh A (2007) Energy consumption pattern of wheat production in India. *Energy* 32(10):1848–1854. <https://doi.org/10.1016/j.energy.2007.03.001>
- Srikanth PA (2016) Farm yard manure. Vanashree <http://www.vanashree.in/fym.htm>. Accessed 28 Dec 2017
- Sun RC, Fang JM, Rowlands P, Bolton J (1998) Physicochemical and thermal characterization of wheat straw hemicelluloses and cellulose. *J Agr Food Chem* 46:2804–2809. <https://doi.org/10.1021/jf971078a>
- Swanaa J, Yanga Y, Behnamb M, Thompson R (2011) An analysis of net energy production and feedstock availability for biobutanol and bioethanol. *Bioresour Technol* 102(2):2112–2117. <https://doi.org/10.1016/j.biortech.2010.08.051>
- Velmurugan R, Muthukumar K (2012) Sono-assisted enzymatic saccharification of sugarcane bagasse for bioethanol production. *Biochem Eng J* 63:1–9. <https://doi.org/10.1016/j.bej.2012.01.001>
- YEP E (2011) India's widening energy deficit. The wall street journal <http://blogs.wsj.com/indiarealtime/2011/03/09/indias-widening-energy-deficit/>. Accessed 28 Dec 2017