THE TECHNICAL, ECONOMIC AND ENVIRONMENTAL FEASIBILITY OF RICE STRAW RESIDUE FOR BIOMASS ENERGY PRODUCTION IN INDIA

By

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ABSTRACT

THE TECHNICAL, ECONOMIC AND ENVIRONMENTAL FEASIBILITY OF RICE STRAW RESIDUE FOR BIOMASS ENERGY PRODUCTION IN INDIA

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This study assessed the feasibility of mobilizing rice straw (paddy residues) for small scale (250kW) bioenergy applications in India by establishing sustainable residue removal rates and cost of supply values for two production regions (Punjab and Haryana). A key objective was to refine the methodology for estimating costs for collection and transportation of rice straw harvesting for bioenergy use. The delivered cost of rice straw retrieved from one hectare of land and transported 10 km to the power plant has been estimated at INR 2.05 (USD 0.03) per kg. Various technological options have been explored for electricity generation from rice straw, and it was found that a gasifier with an internal combustion engine designed to operate on 100% producer gas is the suitable option for installing a 250kW grid connected power plant. The average power purchase agreement (PPA) price in India varies from INR 6.50 to INR 7.50 for biomass gasification based power plant, but at the price the proposed system is not economically viable. In order to assess what PPA price would be required for financial viability INR 9 has been assumed, which is higher prices than the market rate in the analysis. At an assumed power purchase price of electricity of INR 9.0 per kWh, the results give an IRR of 22% with positive net present value of the 10-year lifetime in Scenario 1 (with MNRE capital subsidy of INR 15,000/kW). For scenario 2 (without subsidy), at the same PPA price, the IRR value is 15%, and the lifetime net present value remains positive. The findings of this research can be utilized by policy makers and power utilities for policy recommendations and business models, respectively, for the development of small scale rice straw based grid-connected power plant across rice-producing states. It is estimated in the study that the deployment of rice straw gasification-based systems is likely to reduce annual greenhouse gas emissions in India by about 605 tCO_2e per 250 kW power plant due to avoided emissions associated with the Indian national electricity grid mix. Further, if 15,000 such plants are installed, then these plants will save approximately 514,000 tCO_2e emissions per year due to open field burning on top of the avoided emissions from displacing power in the national grid mix. Additionally, establishing sustainable rice straw supply systems in Indian can lead to positive socio-economic change in rural areas of India.

Keywords:

Rice Straw, Agri-residues, Gasification, Renewable Energy, Levelized Cost of Energy, Greenhouse Gas Emission.

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ABBREVIATIONS

Readers may find helpful the following list of abbreviations used in the thesis.

ARB	Air Resource Board
BCR	Benefit Cost Ratio
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CO	Carbon Monoxide
CHP	Combined Heat and Power
DOE	U.S. Department of Energy
EAI	Energy Alternatives India
EPA	Environment Protection Agency of United States
ESCO	Energy Service Companies
GHG	Greenhouse Gas
GWP	Global Warming Potential
IC	Internal Combustion Engine
IPPs	Independent Power Producers
IREDA	Indian Renewable Energy Development Agency Limited
IRRI	International Rice Research Institute
kW	Kilo Watt
kWh	Kilo Watt Hour
kg	Kilogram
LCOE	Levelized Cost of Energy
MNRE	Ministry of New and Renewable Energy Authority
N_2O	Nitrous Oxide
NPV	Net Present Value
SHG	Self-Help Group
SGR	Straw Grain Ratio

INTRODUCTION

In the developing world, open field burning continues to be the lowest cost, most straightforward, and most hygienic means of size reduction and clearance of combustible agricultural waste (Shafie, 2016). However, this activity not only exposes humans to health hazards of toxic emissions but also contributes to global warming and climate change due to emission of greenhouse gases like CO_2, N_2O and CH_4 (Gadde, Menke, & Wassmann, 2007). Aside from causing pollution, burning causes nutrient losses in the material such as 80% of nitrogen, 25% of phosphorus, and 21% of potassium along with a loss in soil organic matter. Open field burning also kills beneficial soil insects and microorganisms (Mandal, et al., 2004).

At present, paddy residues are burnt in many countries as an easy solution for waste disposal (Shafie, 2016). Research on biomass residue in Canada stated that market supports and policy endorsement have a huge impact on the variety of bio-energy feedstock and GHG emissions (Tingting & Brian McConkey, 2014).

It is estimated that 97 Mt of rice straw are produced in India each year, and 14 Mt of straw are estimated to be burnt in the field (Rajan & Sheshagiri, 2007). The utilization of this feedstock can be sustainably achieved using modern technology coupled with energy policy (Zhu & Zhuang, 2012). Researchers found paddy residue as one of the most promising lignocellulosic biomass resources for a variety of energy applications such as electricity generation and process heat (Suramaythangkoor & Gheewala, 2010).

The aim of this analysis is to extensively review the potential of paddy residue for electricity generation. The analysis will consider energy, economic and environmental dimensions of this issue. In this thesis, the management logistics of paddy residue utilization as a fuel for a gasification based power plant are analyzed to estimate the cost-effectiveness and environmental impacts of this approach. The analysis includes a review of the potential of rice straw production in India, available power generation technologies, and existing policies.

The scope of the research and analysis covers following topics:

- Topic 1 - Determination of the delivered cost of rice straw to nearest available power plant.
- Topic 2 - Determination of the technical and economic potential of the gasification method for electricity production using rice straw.
- Topic 3 - Determination of GHG emissions due to open field burning of rice straw in India.

Throughout the thesis, the author made attempts to define and standardize terms that are used in this study. The research paper includes a literature review section, a method section to evaluate topics 1, 2 and 3, a result section, discussion, conclusion, and policy recommendations for paddy residue utilization in energy industries.

LITERATURE REVIEW

The literature review section provides a relevant overview of rice straw utilization for electricity generation in India. The section provides a description of rice straw applications in India, annual yield, prevailing methods adopted for electricity generation using agriculture-residues, and environmental impacts due to open field burning.

Definition of Open Field Burning of Agriculture Residue

According to a North Dakota Department of Health, Division of Air Quality report “Open burning is defined as the burning of any matter in such a manner that products of combustion resulting from the burning are emitted directly into the ambient or surrounding outside air without passing through an adequate stack, duct or chimney. It includes a wide variety of activities such as burning of crop residues in agricultural areas, use of firewood in cooking stoves, and backyard combustion of domestic and industrial wastes” (NDDH-DAQ, 2007).

In an Indian context, the rice-wheat cropping system (RWCS) is a dominant cropping practice, which involves growing rice and wheat in rotation throughout the year where rice and wheat are either grown in the same plot in the same year or in different plots in the same year or in the same plot in different year. According to a study by R. Gupta (2012), the RWCS accounts for nearly one-fourth of the crop residue production in India. Uttar Pradesh, Punjab, Haryana, Bihar, Madhya Pradesh, and Himachal Pradesh have the largest areas under this system among the Indian states. Rice is grown during the warm, humid season between June and October, and wheat is grown in the cool, dry season between November and March. Consequently, field clearing by burning occurs on a biannual basis (Gupta, 2012).

Figure-1 shows open field burning of rice straw in a rice field near Jalkheri Village, Fatehgarh Sahib District, Punjab, India. While open field burning is a low cost method to clear the field from agricultural waste for sowing next crop. Open field burning actually results in net nutrient loss of soil (Mandal, et al., 2004).

Figure 1 Open field burning of rice straw in a rice field near Jalkheri Village, Fatehgarh Sahib District, Punjab state, India (picture was taken on 17th October 2007).
Source: (Gadde, Bonnet, Menke, & Garivait, 2009)

Use of Rice Straw in India

In South and Southeast Asian countries rice straw and husk are considered as waste products, and they are either dumped into large water bodies or burned in the field (Lim, Manan, Alwi, & Hashim, 2012). The burning of rice straw causes GHG emissions, contamination, and pollution. With the development of recent technologies, there are various ways to process and utilize rice straw.

Figure-2 shows different options for management of rice straw and rice residues. Rice straw management can be classified as in-field and off-field management (Lim, Manan, Alwi, & Haslenda, A review on utilisation of biomass from rice industry as a source of renewable energy, 2012). In in-field management, there may be three options:

- Burning: Burning is a simple process to remove the left overs of paddy crops.
- Manuring/composting: This can be done in two ways. Either the stubbles are mixed with the soil to maintain soil fertility, which is a common practice in the rice growing areas of the country, or the unused and spoiled straw (left by animals, spoiled during storage, or waterlogged and unfit for consumption) is mixed with dung and allowed to form compost which is then used in fields as manure.
- Fodder: Although rice straw is not a good quality fodder in terms of protein and mineral content, and it is high in lignocellulose and insoluble ash, rice straw is commonly used as a basal diet food for animals in areas where green fodder is scarce. In areas such as Punjab, Haryana and Western Uttar Pradesh, wheat straw

is preferred over rice straw. Farmers in these areas mostly cultivate green fodder and mix it with wheat straw (which need not be chaffed and is commonly available in that form) and feed it to the animal which is labor saving, while rice straw chaffing is labor intensive (Singh, Sana, Singh, Chandra, & Shukla, 1995).

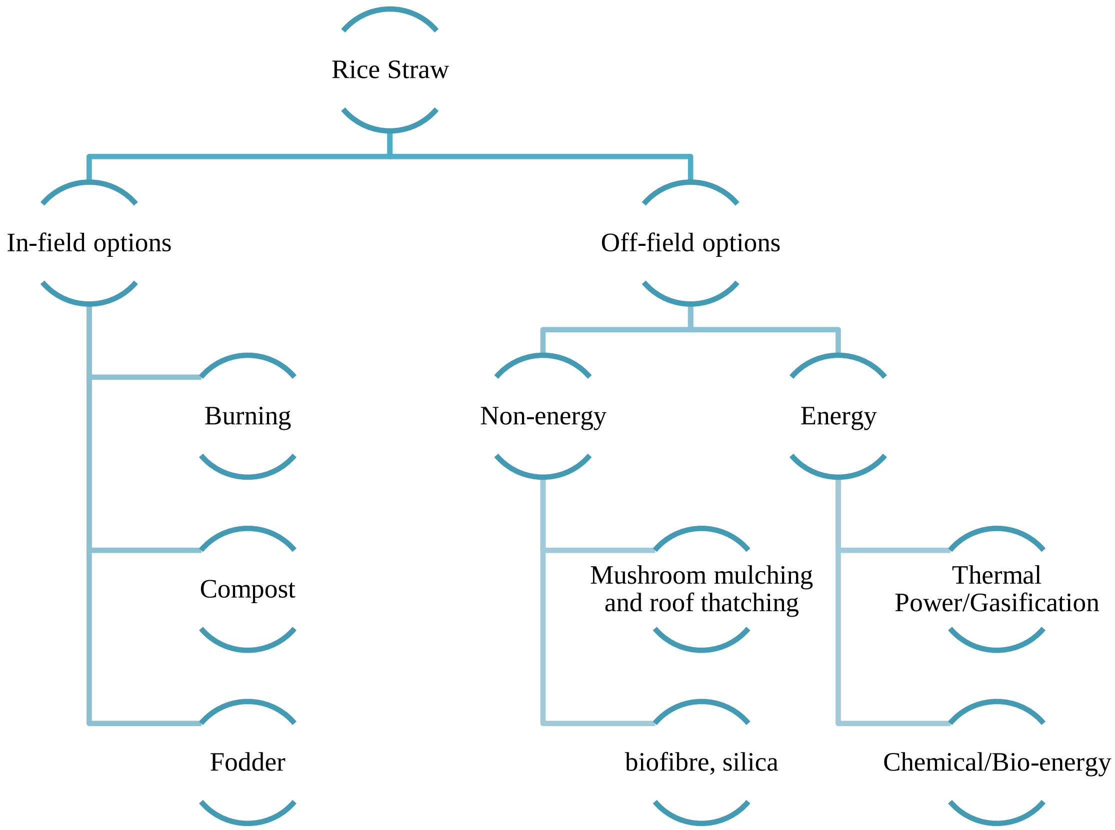

Figure 2. Diagram of the uses of rice straw in various sectors.

In off-field management option, rice straw can be used either in the energy sector or in non-energy sectors. In the energy sector, rice straw can be burnt directly to generate heat, and can also be gasified through a chemical process to convert it into a combustible synthetic gas (Das, 2014) . In non-energy sector applications, rice straw widely used for roof thatching in villages in rice growing areas. Chaffed rice straw is used for bedding material in deep litter poultry. Rice straw can also be used for mushroom culture and packing materials (packing material for transport of goods to avoid breakage/spoilage). Further, rice straw can be used industrially to manufacture paper, strawboard, alcohol, hats, mats, ropes, baskets, etc. (IRRI, 2017).

Existing Methods to Generate Electricity from Rice Straw

Countries like India, a major producer of rice, have abundant quantities of rice residue. Residues like stubbles, straw and husks can be used as an energy source in thermochemical conversion processes such as gasification and combustion (Yoon, Son, Kim, & Lee, 2012) or in bioconversion processes for production of bioethanol (Karimi, Emtiazi, & Taherzadeh, 2006) and biogas production (Teghammar, 2012). The ash produced from gasification and combustion processes can be used as a supplementary material in cement and ceramic manufacturing (Zain, Islam, Mahmud, & Jamil, 2011), and the spent material from bioconversion can be used as an animal feed (Bisaria, Madan, & Vasudevan, 1997).

Combustion is used to convert biomass energy into heat, mechanical power, or electricity. Net conversion efficiencies range from 20% to 40%. The higher efficiency values may be obtained when the biomass is co-combusted in coal-fired power plants (Broek, Faaij, & Wijk, 1996).

Gasification is a process which converts biomass into a combustible gas mixture of carbon monoxide, hydrogen and methane. The produced synthetic gas is characterized by a low calorific value. It can be burnt to produce heat and steam or used in gas turbines or internal combustion engines to obtain electricity. Conversion efficiencies of up to 50% may be reached if a biomass integrated gasification/combined cycle power plant is utilized (Solantausta, Bridgwater, & Beckman, 1995). Although many biomass gasification processes have been developed commercially, the fluid bed configurations are being considered only in applications ranging from 5 to 300 MW. Electricity generation using synthetic gas is carried out using internal and external combustion engines or gas turbines (Overend, 1998).

Fermentation is used to produce ethanol from biomass containing sugar. Usually sugar is extracted through a crushing process; then it is mixed with water and yeast and kept warm in a fermentation tank. The yeast breaks down the sugar, converting it to methanol. A distillation process removes the water and produces concentrated ethanol which is drawn off and condensed into a liquid form (Demirbas, 2001).

Anaerobic digestion is the conversion of biomass into biogas, which is mainly composed of methane and carbon dioxide, by means of bacterial action in the absence of oxygen. This is a commercially proven technology widely used for treating high moisture content biomass such as municipal solid waste MSW (McKendry, 2002).

Yield and Costing of Rice Straw

The yield of rice straw depends on the Straw to Grain Ratio (SGR[1]). The SGR method has been used to calculate field straw availability (Gadde, Bonnet, Menke, & Garivait, 2009). SGR varies with seasons, locations, and cutting heights. A range of SGR ratios of 0.45, 0.59, and 0.75 is reported in other studies such as "Biomass energy potential in Thailand and "Rice straw as a renewable energy source in India, Thailand, and the Philippines. In the article "Rice straw as a renewable energy source in India, Thailand, and the Philippines", an average SGR ratio of 0.75 was used to estimate straw residue yields per area through following equation:

Average straw yield (t/ha) = Average product yield of paddy (t/ha) x SGR x percentage of surplus straw production x QSFB (Equation 1)

Where QSFB is the proportion of rice straw subject to open field burning (%). The quantity of rice straw generated in India was estimated by multiplying rice production data by a factor of 1.5 (constant) to translate it in terms of rough rice (Narciso & Hossain, 2007). The rice production data for India were sourced from the Directorate of Rice Development (DRD, 2006) and amount to 86 Mt/year, which is equal to 130 Mt of rough rice per year. This is an average value calculated over a six-year period from 1999/2000

[1] Straw production levels for paddy and wheat crops are estimated based on measurements of grain production.

to 2004/2005. Using the equation shown above, it was estimated that 97 Mt of rice straw were produced in India each year. The article by Narciso and Hossain from 2007, data on current uses from the National Biomass Resource Assessment (NBRA) program that indicated that 23% of the total rice straw produced in the field, or 22 Mt, was surplus (subject to open field burning) (Narciso & Hossain, 2007). Although, this percentage of surplus amount of rice straw may have been decreased or increased in current scenario, but in this study the same percentage has been used for calculation of amount of rice straw subject to open field burning. The intensive rice–wheat crop rotation in these states does not allow retaining the crop residues in the field for an extended duration, hence they are often open burnt (see Figures 1 and 2).

In India, the study by Gadde et al. (2009) reveals that the annual quantity of rice straw open burnt (13.92 Mt) would represent about 15% of the total amount of crop residues (84 Mt) subject to open burning as estimated in an article on biomass burning in Asia (Streets, Yarber, Woo, & Carmichael, 2003). The total amount of crop residue generated in India is estimated at 350×10^6 kg per year, of which wheat residue constitutes about 27% and rice residue about 51% (Kumar, Kumar, & Joshi, 2015). The states of Punjab and Haryana alone contribute 48% of this total, and the majority of the material is subject to open field burning (Kumar, Kumar, & Joshi, 2015). Uttar Pradesh contributes 14% of the total rice straw surplus, which is also entirely subject to open field burning (Rajan & Sheshagiri, 2007).

Environmental Impact of Open Field Burning of Rice Straw

According to the article by Gadde et al. (2009), open field burning is defined as an uncontrolled combustion process during which species such as CO_2, nitrous oxide (N_2O), CH_4, CO, non-methane hydrocarbons (NMHC), NO_x, SO_2, and particulate matter (PM) are emitted. Particulate Matter (PM), because of its adverse impacts on human health and the environment, can be further categorized as Particulate Matter less than 2.5 micron (PM2.5) and Particulate Matter less than 10 micron (PM10). Polycyclic Aromatic Hydrocarbons (PAHs) and Polychlorobenzodioxins (PCDDs), and Polychlorodibenzofurans (PCDFs) are also of importance due to their toxicity and carcinogenic nature. Among those, the greenhouse gases (GHGs) of importance are CO_2, N_2O and CH_4 which contribute to global warming and climate change (Gadde, Bonnet, Menke, & Garivait, 2009).

Further, agricultural residue burning has been identified as one of the major global sources of atmospheric pollution (Jimenez, 2002). It releases large amounts of dense smoke which contains chemical compounds and particulate matter that affect air quality, and it is linked to health and visibility problems. This smoke contains black carbon, which is the second largest contributor to global warming after carbon dioxide emissions (Ramanathan & Carmichael, 2008). The burning of agricultural residue causes smog formation, which can lead to respiratory disorders, lung cancer and other health problems.

Rice Straw Burning Practice in India

In India, according to the National Biomass Resource Assessment (NBRA), approximately 87% of rice straw is being used in different sectors and around 23% of rice straw is burnt in open fields. The smoke coming from burning fields encompasses nearby areas and causes a rise in pollutants in the atmosphere. The New York Times reported "how straw burning had contributed immensely to the particulate levels reaching 688 micrograms per cubic meter in Delhi on October 31, 2016, more than ten times the safe limit." "The farmers claimed that they burnt straw because they could not afford to dispose of the material any other way" (Anand, 2016). Figure 3 is a picture taken from India showing a farmer burning a harvested wheat field on the outskirts of Jalandhar, India. The results from study suggests that farmers in India burned 116 million metric tons of crop residue, accounting for about 25% of black carbon, organic matter, and carbon monoxide emissions, 9-13% of fine particulate matter (P.M 2.5) and carbon dioxide emissions, and about 1% of sulfur dioxide emissions. An important source of atmospheric pollution in the Indo-Gangetic plains is biomass burning of agricultural field residue such as stalks and stubble during wheat and rice harvesting periods (Gupta, 2012).

Figure 3 A farmer burned a harvested wheat field last month on the outskirts of Jalandhar, India. Source: (NewYork Times, 2016)

Current Policy of Government of India on Biomass Based Power Generation

The Ministry of New and Renewable Energy is trying to promote and encourage biomass gasifier based power plants for producing electricity using biomass/agriculture resources such as wood chips, paddy residues, wheat residues, cotton stalks and other agro-residues. The main components of the biomass gasifier program are:

- Distributed off-grid power for rural areas
- Captive power generation applications in small and medium scale industries.
- Tail end grid connected power projects up to 2 MW capacities.

The focus of the biomass gasifier program is to meet electrical demands of small and medium scale industries, rural households, and underpowered areas of the electrical grid. The use of these systems therefore can help reduce the use of conventional fuels such as coal and diesel. The central government also gives financial support for setting such as subsidies on capital cost for biomass gasifier based power plants with generation capacity up to 2 MW that are connected at the tail end of grid to provide various benefits such as voltage support, access to electricity in villages, and encouragement to farmers to reducing burning of agri-residues in field. The program encourages involvement of independent power producers (IPPs), energy service companies (ESCOs), industries, co-operatives, panchayats, SHGs, NGOs, manufactures, and social entrepreneurs to invest in and promote this technology (MNRE, 2011). Due to government efforts, about 150 MW equivalent biomass gasifier systems have been set up for grid and off-grid projects. According to government data, more than 300 rice mills and other industries use gasifier systems to meet their electrical and thermal demands (MNRE, 2012). In addition, about 70 biomass gasifier systems provide electricity to more than 230 villages in the country (TERI, 2016). The Government of India provides subsidies on various gasifier based projects across the country to support development of gasifier based technology (MNRE, 2011).

CASE STUDIES

As per the 2011 census of India, there are a total of 640,867 villages in India. As of April 1, 2015, according to Indian government data, 18,452 of these villages are still un-electrified (Bansal, 2017) due to power shortages, lack of grid infrastructure, or infeasibility of extending the grid to reach the village. Electrifying these villages with renewable energy options such as solar photovoltaics, micro-hydro, wind, and biomass gasification is a promising alternative. Among these options, agricultural residue-based electrification has good prospects in the Indian context due to its widespread availability in rural areas of the country where these villages are located. Agri-based power generation alternatives can play a vital role in the rural electrification where agriculture is the principal activity (Ramchandra, Joshi, & Subrmaniam, 2000). Given below are some case studies where agricultural residue gasification-based power generation systems are utilized as an option for rural electrification in villages in India.

Grid Connected Biomass Power Plant in the State of Karnataka

Biomass Energy Rural India (BERI) has installed a 500-kW capacity system in Kabbigere village. The system comprises of two 100 kW gasifier systems and one 200 kW using 100% producer gas, and another 100 kW with dual fuel (Jain & Srinivas, 2012). It was reported that these plants together have generated 1,520,000 kWh of electricity as of June 2012. In addition, two more gasifier-based power plants of 250-kW capacity each have been installed in Seebanayanapalya and Borigunte. The power generated is fed into the BESCOM (Bangalore Electricity Supply Company) grid. The BERI Society and Tovinakere Grama Panchayat have signed a first-of-its-kind PPA (power purchase agreement) with BESCOM to sell the power produced to the state power utility at INR 2.85/kWh ($0.04/kWh) (Jain & Srinivas, 2012).

Island-based installations in the Sundarbans in the state of West Bengal

Two remote islands in the Sundarbans in the state of West Bengal, Gosaba and Chottomollakhali Islands, have been electrified by the West Bengal Renewable Energy Development Authority (WBREDA) by installation of a biomass gasifier generation system. Gosaba Island is located in “24-Paraganas” District, which is 115 km from Kolkata. The island has five 100-kW gasifier generator systems. To meet the systems’ fuel needs, an energy plantation was established using 100 hectares of wasteland. The yield from this plantation is 10 tons of biomass per hectare per year. A cluster of five villages with a total population of approximately 10,000 has received electricity from this installation. The generators are of dual fuel type, and they consume 70% producer gas and 30% diesel at full load. The specific biomass consumption is 0.8 kg of dry wood/kWh, and the units are operated for 16 h each day. The tariff structure is INR 5.60/kWh ($0.08/kWh) for domestic users, INR 6.75/kWh ($0.10/kWh) for commercial users, and INR 8/kWh ($0.12/kWh) for industrial users. The total capital cost of installation was INR 9.5 million ($146,447), and this operation has provided direct and indirect employment to about 84 people (Buragohain, Moholkar, & Mahanta, 2010).

COLLECTION AND SUPPLY OF RICE STRAW

Rice straw is a by-product of paddy crops. It can be separated from the grains either manually, using stationary threshers, or by using a combine harvester. In traditional manual harvesting, rice straw is collected from the field and saved for other uses. However, in recent times wide adoption and use of combine harvesters that leave the rice straw spread out in the field has made gathering of straw a tedious and labor intensive task. This has made manual collection of rice straw unfeasible and therefore, the left over straw is generally burnt in the field. This practice not only leads to environmental pollution but also causes a considerable economic loss of biomass. A report published by the All India Coordinated Research Project on Farm Implementation and Machinery states that straw combines and straw balers are a few farm machineries that collect the scattered rice straw from the field (Bansal & Mukesh, 2010). In this study, straw combines have been considered for gathering rice straw from the field. As shown in Figure 4, a straw combine is pulled by a tractor, and the straw combine gathers the straw and leftover grains in the back of trailer. The straws collected are finely chopped. Typically, straw combines gather 80% of the rice straw from the field. A straw combine essentially consists of three main units, including a stubble cutting and collecting unit, a feeding unit, and a straw bruising unit. Typically, the straw combine is pulled by 35 to 45 hp tractor with an attached trolley. The filled trolley is then unloaded near the plant site (Bansal & Mukesh, 2010).

Figure 4. Image of Straw Combine. Source: (Mahmood, Ahmad, & Ali, 2016)

Yield of Rice Straw

The method of SGR (Straw to Grain Ratio) has been used to calculate the field straw availability. The grain to straw ratio in India varies between 1:1.3 and 1:3 (FAO, 2000). In this research paper, a SGR of 0.75 (i.e. 1:1.33) has been considered for calculating rice straw yield per hectare in India. Using the SGR value, the following equation is used to estimate the quantity of rice straw subject to open burning:

$$\mathrm{QSSFB} = \mathrm{PRR} \times \mathrm{SGR} \times \mathrm{QSFB} \qquad \text{(Equation 2)}$$

Where,

QSSFB = Quantity of rice straw subject to open field burning in Gg/year;

PRR = Rough Rice Production in Gg/year (Narciso & Hossain, 2007)

PRR can be calculated using the following equation:

$$\mathrm{PRR} = 1.5 \text{ x Average annual rice production or rice production per hectare}$$

SGR = Straw to Grain Ratio (0.75);

QSFB = Proportion of rice straw subject to open field burning (%).

As per National Biomass Resource Assessment Program, 23% of rice straw is estimated to be burnt in open field, which is approximately 26 million tons per year. The data for rice production are taken from Department of Agriculture, Cooperation & Farmers’ Welfare (India) to calculate the average annual production of rice (Table 1).

The average annual production of rice in India from 2010 to 2015 was 103.62 million tons. The yield (per hectare) of paddy crops varies with soil fertility, moisture content, rainfall, farming techniques, and locations. In this study, the average yield across the country has been considered for the calculation of the delivered cost of rice straw.

Table 1. Yearly Rice Production in India from 2010 to 2015. Source: (Department of Agriculture, 2016)

Year	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	Total (Mt)
Kharif[2]	80.7	92.8	92.4	91.5	90.9	448.3
Rabi[3]	15.3	12.5	12.9	15.2	13.9	69.8

Using the above equation, it has been found that average annual rice straw production is 116.57 million tons. The average yield of rice per hectare (2.3 ton/hectare) data has been taken from the Directorate of Economics & Statistics, Department of Agriculture & Cooperation (India) has been used. It is found that the per hectare yield of rice straw is approximately 2.6 tons.

The cost of rice straw collection was calculated based on the customized hiring of a straw combine pulled by tractor, customized hiring of a tractor for transportation, fuel consumption, and labor for all related operations, including loading and unloading the

[2] In India, the kharif season varies by crop and state, with kharif starting at the earliest in May and ending at the latest in January, but is popularly considered to start in June and to end in October.

[3] The rabi crops are sown around mid-November, after the monsoon rains are over, and harvesting begins in April/May. The crops are grown either with rainwater that has percolated into the ground or with irrigation.

rice straw. The study assumes the plant is located within a distance of 10 km from the field because within a 10-km radius there is enough rice straw to power a plant with a 250 kW capacity.

Assumptions

This section covers the assumptions included for calculating delivered cost of rice straw.

- Customized hiring of a straw combine for collection of rice straw from fields: The cost of hiring a straw combine pulled by a tractor has been assumed as INR[4] 1500/hectare ($23.12/hectare) (Bansal & Mukesh, 2010).
- Fuel requirement by tractor for rice straw collection: The quantity of fuel required by the tractor used by for the straw combine to collect rice straw from one hectare is 9.74 liter. Therefore, the total cost of fuel would be 9.74 liter/hectare x INR 54.49 ($0.84) (cost of one liter of fuel), which is equal to INR 530.73 ($8.17).
- Customized hiring of a tractor for collection and transportation of rice straw: The cost of hiring a tractor has been assumed as INR 160/hour ($2.5/hour) (Bansal & Mukesh, 2010). It has been assumed the tractor would serve only for 6 hours daily. Therefore, the total cost per day would be INR 960 ($14.8/kWh).
- Fuel requirement for transportation: Typically, a 35 HP tractor uses 3 liters of diesel for one hour of operation. An average speed of 30 kilometers per hour has been used to evaluate the time consumed during transportation. The time

[4] INR is Indian rupees and one U.S. Dollar (USD) is equivalent to INR 64.87 (as of date 10/31/17). Paisa is 100th part of one INR.

consumed in one trip helps estimate the total hiring cost for transporting rice straw produced in one hectare. In this study, it has been assumed that the average distance covered by the tractor from the field to the power plant is 10 km; therefore, in two round trips (for collection of rice straw from one hectare of land) the total distance covered is 40 km. The total running of tractor would be the total distance travelled divided by the average speed of the tractor. Therefore, the cost of fuel has been calculated by multiplying the per hour consumption of diesel by the prevailing cost of one liter of diesel and the number of running hours. The total cost of diesel per day during field work period has been calculated to INR 218 ($3.36).

- Labor required for loading and unloading of rice straw: According to the Ministry of Human Resources of India, per day cost of hiring unskilled labor is INR 513 ($7.90) (Singh A. K., 2017). It has been assumed in the study that two days of labor are required for loading and unloading 2000 kg of rice straw. Therefore, the total labor cost would be INR 513 per day x 2 days = INR 1026 ($15.81) per hectare.

ECONOMICS OF GASIFIER AND INTERNAL COMBUSTION ENGINE BASED POWER PLANT

There are two viable gasification technologies for commercialization of electricity production from biomass: (1) biomass gasification coupled with an internal combustion engine operating on producer gas and (2) boiler-steam turbine systems. The technology of biomass gasification is suitable for small scale distributed and decentralized generation in remote villages (Buljit, et al., 2010). Technology option suitable for a small scale gasification power plant and sizing have been discussed below in detail.

Technology Option and Sizing

Electricity can be generated through several approaches using thermochemical gasification of biomass (IRENA, 2012). Following are some examples:

- Pressurized gasification with a gas turbine in a combined cycle system
- Atmospheric gasification with a gas turbine or an engine generator
- Combustion with a Rankine steam cycle

Thermochemical gasification is a process in which the feedstock such as biomass/agri-residue undergoes partial oxidation at moderate to high temperature to produce a synthetic gas. The major compositions of producer gas are H_2 (18-23%), CO (17-20%) CH_4 (3-4%), CO_2 (13-14%), and N_2 (balance of gas) (Sadaka, Ghaly, & Sabbah, 2002). Air, oxygen, and steam are generally used to carry out partial oxidation (Couto, Rouboa, Silva, Monteiro, & Bouziane, 2013). Air gasification is a widely used technology because it avoids the costs and hazards associated with oxygen gasification, and it also avoids the complexity and cost of multiple reactors associated with steam or pyrolytic gasification systems. When solid biomass is heated to 300-500°C in the absence of an oxidizing agent, the fuel breaks into solid char, condensable hydrocarbons or tar, and gases. The relative amounts of produced gas, liquid, and char depend mostly on the rate of heating and the final temperature. The gas composition and quality depends on factors such as feedstock composition, moisture content, temperature, and the amount of air present during oxidation. During the production of combustible gases, the liquid products from the pyrolysis step, which are known as tars, are mixed with the gas (Bridgewater, 1995).

Figure 5, below, is a schematic diagram of gasifier based power generation system. The feedstock is fed into the gasifier, where it is oxidized to generate producer gas. Since the gas contains tar and small particles, it is cleaned and filtered using a cyclone and scrubber. The cleaned gas is then fed to an engine, where it acts as a fuel for firing the engine, which, in turn, creates mechanical movement of the crank shaft. The alternator coupled to engine gets a rotational movement that enables electricity generation.

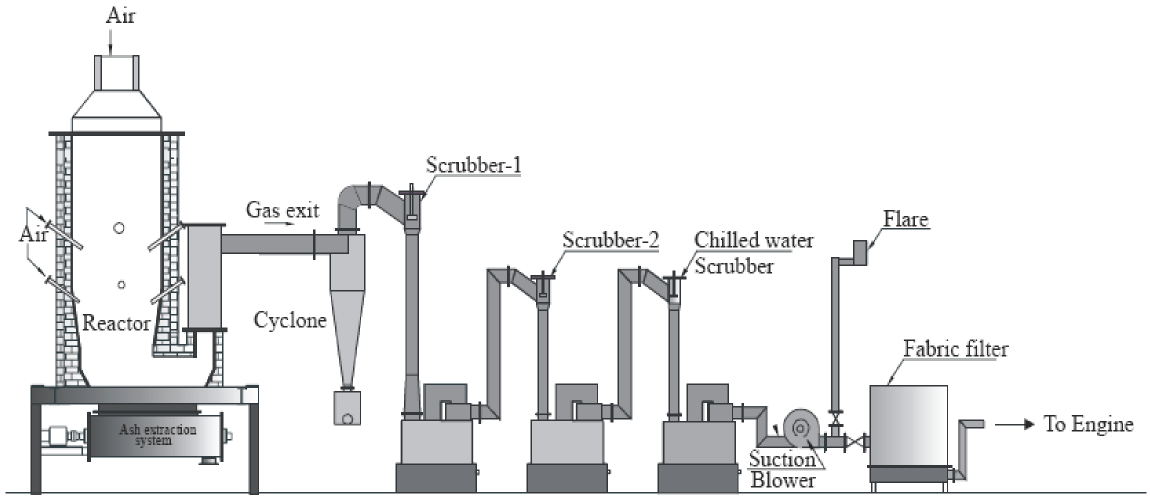

Figure 5 Biomass downdraft gasifier system. Source: (Gandhi, Kannadasan, & Suresh, 2012)

While biomass gasification-based power production provides a number of benefits, especially to remote electricity needs, it is imperative that it is economically sustainable to operate. The primary cost components of a biomass gasification system include feedstock purchases, capital costs (gasifier + gas engine + supporting equipment + land + installation), and operating expenses (including operator labor, maintenance, and repairs). According to a report published by IRENA, the LCOE range for gasifiers is very wide. This is due in part to variations in feedstock costs but also because fixed bed gasifiers are a more proven technology that is cheaper than circulating fluid bed (CFB) or bubbling fluid bed (BFB) gasifiers (IRENA, 2012). The LCOE for gasifiers varies from USD 0.065/kWh (fixed bed gasifier with low-cost bioenergy fuel) to USD 0.24/kWh (a small-scale gasifier with an internal combustion engine as the prime mover) for systems that would be suitable for off-grid applications or mini-grids. However, although this is expensive compared to grid-scale options, it is more competitive than a diesel-fired solution (IRENA, 2012). The lifetime of the project assumed in the study is 10 years. In the article "Techno-Economic study of a Biomass Gasification Plant for the Production of Transport Biofuel for small communities" by Mustafa et al., the authors have considered a lifetime of 10 years for a gasification plant (Mustafa, Calay, & Mustafa, 2016). In another study, "An assessment of a Biomass Gasification based Power Plant in the Sunderbans" by Kakali Mukhopadhyay, a 15-year lifetime has been taken (Mukhopadhyay, 2004).

The assumptions used in this study are described in the following section.

<u>Assumptions</u>

- Rated capacity of proposed power plant: A 250-kW gasifier based power plant has been proposed in this study. Such plants are easy to install and operate and require less land in comparison to a MW-scale plant.
- Capital cost: The total investment cost, or capital expenditure (CAPEX), consists of the equipment (prime mover and fuel conversion system), fuel handling and preparation machinery, engineering and construction costs, and planning. It can also include grid interconnection, roads, and other new infrastructure or improvements to existing infrastructure required for the project. In this study, it has been assumed that the capital expenditure includes the cost of grid interconnection infrastructure (IRENA, 2012). As per Energy Alternatives India (EAI), an independent organization, the cost

of a 1 MW power plant project is INR 55,000,000 ($847,850) (Sreevatsan, 2011). For the current analysis, the cost of a 250-kW plant has been assumed as one-fourth of the cost of 1 MW plant. However, it is not necessarily true that the cost would reduce to one fourth due to economies of scale. Hence, a sensitivity analysis has been done in the discussion section to study to consider the potential impact of a higher cost of plant.

- Operation and maintenance cost: According to the report "Biomass Gasification Based Power Production in India" published by EAI, the operation and maintenance cost (excluding the cost of biomass feedstock) of gasifier and IC engine based power plants is approximately INR 0.75 per kWh ($0.01/kWh) (Sreevatsan, 2011). In this research paper, an operation and maintenance cost of INR 0.75 per kWh ($0.01/kWh) has been taken for calculation of the levelized cost of energy.
- Annual operating hours: The proposed plant can be run for 12 hours a day, with two days of planned maintenance in a month. Based on these numbers, the total operating hours in a year would be 4,092 hours. Therefore, in this study 4,092 hours of annual operation have been assumed for the economic analysis of the plant.
- Annual rice straw consumption: Typically, to generate one kWh of electricity, 2.4 kg of rice straw are required. This assumes an operating efficiency for the gasifier based power plant of 10% (Mustafa, Calay, & Mustafa, 2016). Therefore, yearly consumption of rice straw has been

calculated by multiplying the amount of rice straw required to generate one unit of electricity by the total electricity generated in one year by the proposed power plant.

- Annual cost of rice straw: The annual cost of the rice straw would be the total annual consumption of rice multiplied by the delivered cost of one kg of rice straw.
- Discount Factor: As per the guidelines of the Central Electricity Regulatory Commission (CERC), which is responsible for energy tariff regulation, the discount factor is equal to the post tax weighted average cost of the capital according to the normative debt to equity ratio (70:30) specified in the relevant regulations (CERC, 2016). The discount factor derived, considering a 12.76% interest rate on the loan component and a 16% rate of return on equity, is 10.70%. The discount factor value has been used to calculate the net present value and the levelized cost of energy in the economic model (CERC, 2016).
- Project loan: Projects related to renewable energy (RE), energy efficiency, energy conservation, and other environmentally sustainable technologies and approaches, including power generation, transmission, renovation & modernization, which are techno-commercially viable, are eligible to obtain finance from the Indian Renewable Energy Development Agency, Limited (IREDA). The eligible sectors are wind energy, hydro power, solar energy, biomass power generation, biomass including bagasse and

industrial cogeneration, waste to energy, energy efficiency and energy conservation, bio-fuel/alternative fuel, hybrid projects with renewable energy technology and new and emerging renewable energy technologies. According to their programs, IREDA shall extend a loan for 100% of eligible equipment cost limited to a maximum of 70% of total project cost. The loan shall be applicable to all grid connected power projects. In this study, it has been assumed that 70% of the capital cost is being availed from IREDA (IREDA, 2014).

- Repayment Period: The repayment periods for the loans, as per IREDA guidelines, shall be a maximum of 10 to 15 years depending on the project cash flows and debt-service coverage ratio (DSCR) (IREDA, 2014). In this paper, a repayment period of 10 years has been considered for the economic calculations.
- IREDA conducts credit ratings for all grid connected projects and assigns grading in a band of 4 grades (I, II, III & IV) based on risk assessment. The interest rate varies from 10.35% to 11.50% with grading. In this study, a conservative 11.50% interest rate has been considered for the economic analysis (IREDA, 2014).
- Subsidy provision by MNRE under the Biomass Gasifier Based Programs: The program supports distributed/off-grid and grid connected power projects in rural areas with 100% gas engines or biomass based

combustion projects. The amount of subsidy provided by MNRE is INR 15,000 per kW ($231) (MNRE, 2011).

METHODS

Cost of Collection and Supply of Rice Straw (Topic 1)

In this study, a Straw to Grain Ratio (SGR) of 0.75 derived from a study by Gadde, et al. (2007) has been used to calculate the per hectare production of rice straw. Following equation is used to estimate the quantity of rice straw subject to open burning:

$$\mathrm{Crs} = (\mathrm{Ccs} + \mathrm{Cfs} + \mathrm{L} + \mathrm{Ctr} + \mathrm{F})/\mathrm{Crf} \qquad \text{(Equation 3)}$$

Where,

Crs = Cost of rice straw per kilogram (INR/kg)

Ccs = Cost of customized hiring of a straw combine per hectare (INR/hectare); The cost of hiring straw combine for collecting straw from one hectare field is

Cfs = Cost of fuel consumed by the straw combine per hectare;

Ctr = Cost of customized hiring of a tractor for transportation per hectare;

F = Cost of fuel required for transporting straw produced from one hectare;

L = Total of labor cost used for one hectare of field;

Crf = Average kilogram of straw collected from one hectare

Economic Feasibility of the Proposed System (Topic 2)

The project evaluation technique (discounted cash flow) has been used to measure the economic feasibility of the power generation system. This technique measures the productivity of the invested capital and returns over life period (project life = 10 years). The value of the costs can be adjusted to the present using economic discounting methods. Comparative measures of capital productivity commonly used in economic evaluation of investment in biomass energy systems are the net present value and the internal rate of return. Two scenarios have been considered in the study. In Scenario 1, the economic calculation takes an MNRE capital subsidy into account, and in Scenario 2 the subsidy has not been considered for the economic calculations.

- Net present value (NPV)

  In this method, the discounted rate / compound rate, which reflects the price of the investment funds, is used to adjust current and future costs and returns to a common point of time (i.e. the present). The costs are subtracted from the returns to obtain the net present values of the system. Positive net present values indicate that the investment may be worthwhile, and the size of the NPV indicates how worthwhile the project is in utilizing the resources to maximize income (Master, 2004). The following expression is used to calculate the NPV:

$$\text{NPV} = \sum_{t=1}^{n} \frac{Rt - Ct}{(1+i)^t}$$

where, R is the returns in the year t; C is the costs in year t, n is the project life; and i is the discount rate in percent.

- Internal rate of return (IRR)

  The internal rate of return means the discounted compound rate at which the present value of returns equals that of costs (Master, 2004). Accordingly, the derived discounted rate (IRR) is compared with the price of the investment funds to know the worthiness of the project.

  The decision profitability criteria are: if IRR >= 1 with positive NPV, the investment may be worthwhile; if IRR < 1, the investment is not worthwhile.

- Levelized Cost of Energy (LCOE): This metric evaluates the net present value of the unit cost of electricity in $/kWh over the lifetime of a generating asset (Master, 2004). It gives an indication of the minimum price that the project must receive to break even.

LCOE in $/kWh = {*(Present value of customer costs) - (Present value of customer benefits)}/* (*Annualized generation in kWh)*

Estimation of Greenhouse Gas Emission from Open Field Burning (Topic 3)

The approach followed to quantify the emissions due to open field burning of rice straw is based on the methodology set by the Intergovernmental Panel on Climate Change (IPCC) guidelines from 2006 and methods described above to quantify the amount of rice straw subject to open field burning. To estimate the amount of air pollutants generated from biomass burning, emissions factors (EF), expressed in terms of the mass of pollutant emitted per unit mass of dry fuel consumed, are used. Following equation is used to quantify air pollutant emissions from rice straw open field burning:

$$\text{TE (Mg/yr)} = (\text{QSSFB x EF x GWP})\ /10^6\ (\text{g/Mg}) \qquad \text{(Equation 4)}$$

Where,

TE = Emission of pollutant in Mg/year;

EF = Emission factor of pollutant species in g/kg of dry straw;

QSSFB = Quantity of rice straw subject to open field burning in kg/ year;

GWP = global warming potential ratio.

Carbon dioxide emitted from biomass burning is considered to have a neutral effect due to its photosynthetic uptake during plant growth. Emission factors specific to air pollutant species emitted from open field burning of agricultural residues are presented in Table 2. These emissions factors and global warming potential values for greenhouse gases were sourced from the U.S. EPA (2014).

Table 2. Emission factors of greenhouse gases from open field burning. Source: (EPA, 2014)

Name of pollutant	CO_2	CH_4	N_2O
Emission Factors (g/kg)	1074.75	0.29	0.04
GWP (100 years)	1	25	298

The primary advantage of gasification-engine systems is that the energy stored in rice straw is converted to heat or fuels through gasification. The carbon dioxide that was taken up during plant growth is released back into the atmosphere. This makes the gasification process CO_2 neutral, and the GHG emissions are almost zero (Castaldi & Butterman, 2009).

The grid mix and GHG emissions factors associated with different sources of electricity generation are sourced from the Central Electricity Authority, India and an IPCC report on renewable energy sources and climate change. The grid mix percentage and emission factors of different power sources is presented in Table 3. Following equation can be used to estimate the avoided GHG emissions caused by power generating sources in India to generate the electricity (i.e. 767,250 kWh/yr[5]) by the proposed gasification based power plant (Moomaw, et al., 2011) (Central Electricity Authority, 2017).

$$\mathrm{TE\ (Mg/yr)} = (\mathrm{E\ x\ GM\ x\ EF}\ /10^{6}\ \mathrm{(g/Mg)}) \qquad \text{(Equation 5)}$$

where,

TE = Total emission of pollutant in Gg/year;

[5] Considering 25 % derating of engine (for producer gas) and 4092 operating hours per year of 250kW power plant will generate 767,250 kWh/yr. *Reference for derating is mentioned in table B.2*

EF = Emission factor of the CO_2e from different power generation facilities in g/kWh

E =Total energy generated in one year (kWh);

GM= Grid mix percentage

Table 3. Grid mix (2016 data) and GHG emissions factor data for India. Source: (Moomaw, et al., 2011), (Central Electricity Authority, 2017)

Types of power sources	Grid mix (%)	Emission factor (CO_2e g/kWh)
Gas based Power plant	4.04	469
Coal Based power plant	76.68	1001
Nuclear	3.2	16
Solar	0.86	46
Mini-hydro	0.54	4
Wind	3.23	12
Biomass	1.0	32.75
Hydro	10.4	4
Diesel	0.05	840

RESULTS

The results section includes the estimated cost of collection and supply of rice straw from field to power plant, economic results estimated for gasifier based power plant, and estimated average annual greenhouse gas emission in India due to open field burning of rice straw.

Topic 1: Estimated Cost of Collection and Supply of Rice Straw

Based on calculations and assumptions presented above (method section), the delivered cost of rice straw retrieved from one hectare of land to the power plant at a distance of 10 km is 2.14 INR/kg / $0.03/kg.

Topic 2: Economic Feasibility of the Biomass Gasification Power Generation System

An economic model for biomass gasification system based power plant has been developed to evaluate the levelized cost of energy, lifecycle cost, and internal rate of return. In the economic model, different PPA prices have been assumed to evaluate the revenue generation from plant, and it was found that at PPA of INR 8.50 ($0.13), Scenario 1 (capital subsidy included) became economically viable with IRR 11%. As shown in Table 4, at INR 9.00 ($0.13), Scenarios 1 and 2 (no capital subsidy included) become economically viable with IRR values of 22% and 15%, respectively.

Table 4. Results of LCOE, lifecycle cost, and IRR

Economic parameters	Scenario 1	Scenario 2
LCOE ($/kWh)	0.120	0.123
Lifecycle Cost ($)	554,356	566,649
IRR (%)	22	15

Topic 3: Net Greenhouse Gas Emissions

In India, from 2010 to 2015, pollution from open field burning of rice straw has contributed significantly to environmental pollution. It has been calculated that 26.81 MT of rice straw is subjected to open field burning. Using the emission estimation model described above, annual emissions of greenhouse gases due to open field burning of rice straw in India have been calculated and are presented in Table 5.

Table 5. Annual GHG emissions from open field burning of 26.81 million tons of rice straw every year.

Name of pollutant	CH_4	N_2O
Emission (g/kg) Factors	0.29	0.04
Global warming potential	25	298
CO_2e emissions per year	(tCO_2e/year)	514,000
CO_2e emissions per ton of rice straw	kg CO_2e/ton	19.17

GHG emission caused by generating 767,250 kWh (i.e., the annual generation from the proposed rice straw gasification power plant) of electricity by prevailing grid mix in India is furnished in Table 6. If the rice straw gasification system is assumed to produce zero GHG emissions and it generates electricity that displaces power from the overall grid mix, then operation of a plant for a year will result in a reduction of approximately 605 tCO_2e in GHG emissions.

Table 6. Total GHG emission to generate 767,250 kWh in India as per grid mix.

Types of power sources	Grid mix (%)	Emission factor (g CO_2e/kWh)	CO_2e emission (tons CO_2e)
Gas based power plant	4.04	469	14.54
Coal Based power plant	76.68	1001	588.92
Nuclear	3.21	16	0.39
Solar	0.86	46	0.30
Mini-hydro	0.54	4	0.02
Wind	3.23	12	0.30
Biomass	0.99	32.75	0.25
Hydro	10.4	4	0.32
Diesel	0.05	840	0.32
		Total emission (tons CO_2e)	605

DISCUSSION

Regarding Topic 1, the delivered cost of rice straw depends on number of parameters, including the customized hiring cost of farm equipment, the labor cost, the distance of the field from the power plant, and the efficiency of the straw combine. According to the model prepared to calculate the delivered cost, two factors, the customized hiring cost of the straw combine and the efficiency of the straw combine, have a significant impact on the price of rice straw. Figure 6 describes the price variation of delivered rice straw with changes in the customized hiring cost of a tractor pulled straw combine. The analysis indicates that a reduction of INR 100 ($1.54) in the customized hiring cost results in a five paise (INR 0.05) reduction in the price of delivered rice straw. A five paise reduction can be significant while collecting the rice straw on big scale.

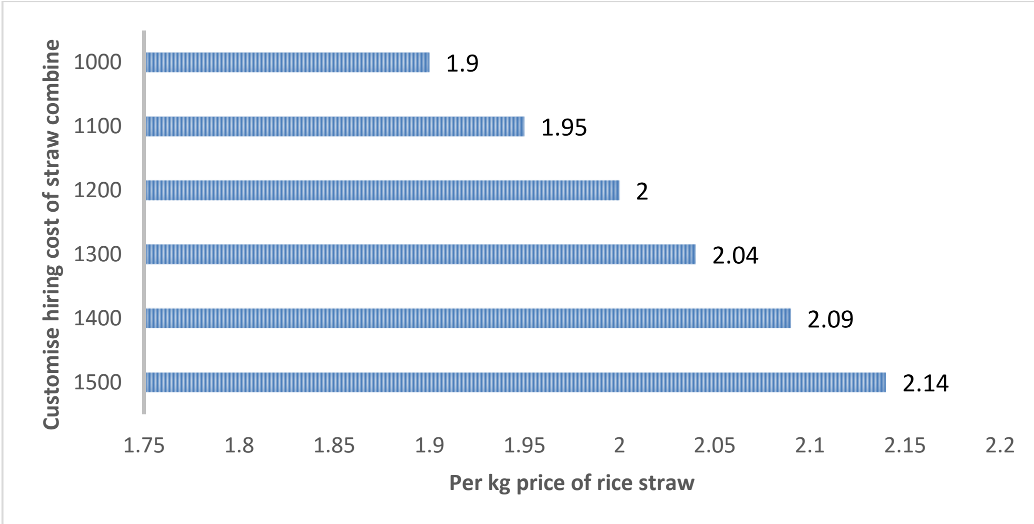

Figure 6. Impact of the customized hiring cost of a tractor-pulled straw combine on the delivered cost of rice straw

Figure 7 is a graphical representation of the variation in the delivered cost of rice straw due to variations in the efficiency of the rice straw combine. Generally, straw combines have a straw collection efficiency of 70% to 80%. If the efficiency of rice straw combine can be increased by introducing modern equipment, then it can significantly reduce the per kg collection cost of the rice straw. For example, if the efficiency of rice straw combine increases to 100%, then the cost of rice straw will be reduced to INR 1.71 per kg ($0.026/kg) from INR 2.45 per kg ($0.03/kg) at 70% collection efficiency.

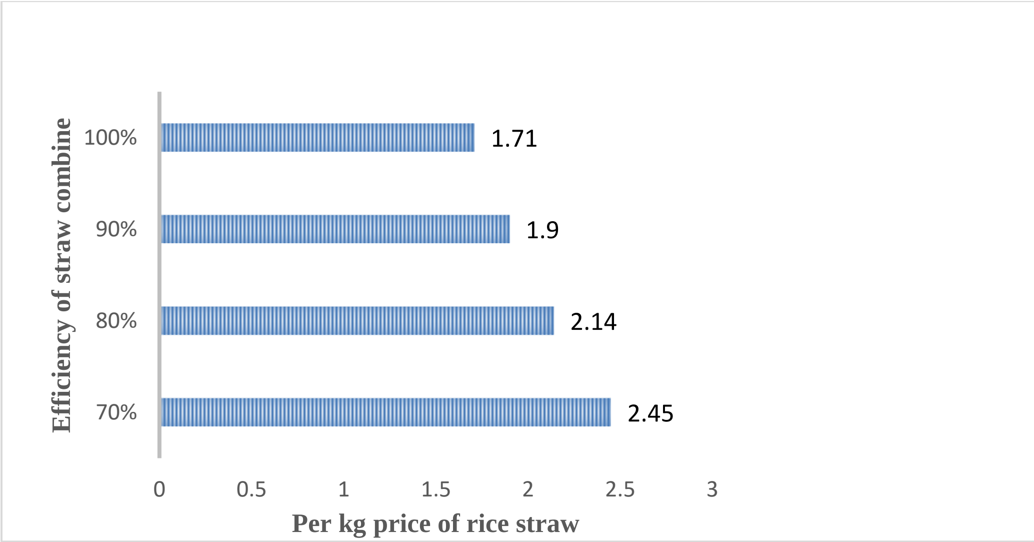

Figure 7. Impact on the cost of rice straw per kg due to variations in the collection efficiency of the straw combine.

Similarly, the other factor which influences the cost of rice straw is the distance of the power plant from the field. Since the cost of hiring a tractor for transportation is on an hourly basis, the distance of the power plant from the field plays an important role in deciding the magnitude of fluctuation in the delivered cost of the rice straw. As the distance increases, the time taken by the tractor for delivery will also increase, thereby increasing the hiring cost of the tractor. Figure 8 shows that an increase in the distance of the power plant from the field increases the delivered cost of rice straw. The analysis indicates that an increase of 5km distance (from field to power plant) results in a six paise (INR 0.05) increase in the price of delivered rice straw.

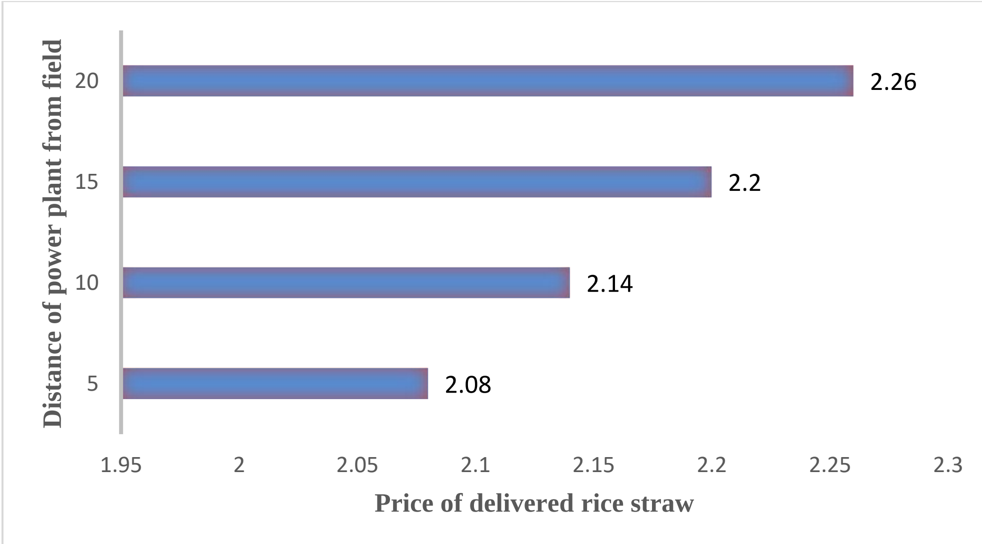

Figure 8. Variation of the price of rice straw with variations in the distance of the power plant from the field

Regarding Topic 2, the potential impacts of the uncertainty inherent in some of key factors that influence the levelized cost of energy are discussed. These factors include the collection efficiency of the straw combine, operation and maintenance costs, the cost of rice straw, and the revenue generation from the PPA.

The principal components of the capital cost of the biomass gasifier system are the biomass gasifier unit (which is essentially a combustion–gasification chamber made of stainless steel), a gas cooling and cleaning unit, and an engine-generator. Other components of the capital cost of the gasifier system include civil construction (room shed and concrete supports for various components of the gasifier systems), biomass preparation and storage units, electrical wiring and piping, the tar removal/cracking system, ash removal facilities, and a distribution network for dissemination of electricity to local consumers. The operating costs of the gasifier system include labor charges, maintenance charges, and replacement of spare parts on an occasional basis. The electricity tariff is also an important parameter in calculating the LCOE because the tariff determines the amount of cash flow during the lifetime of the project.

As per CERC, the applicable tariff rates for Financial Year 2016-17 for different states are presented in Table 7.

Table 7. Applicable tariff rates (PPA rates) for biomass gasifier projects in India (CERC, 2016)

States of India	Applicable tariff (FY-2016-17) (INR/kWh)	Applicable tariff (FY-2016-17) ($/kWh)
Andhra Pradesh	6.51	$0.10
Haryana	7.10	$0.11
Maharashtra	7.21	$0.11
Punjab	7.33	$0.11
Rajasthan	6.44	$0.10
Tamil Nadu	6.44	$0.10
Uttar Pradesh	6.59	$0.10
Others	6.81	$0.10

In the economic model, the above-mentioned power purchase agreement tariffs have been assumed to calculate the LCOE and IRR, but the results are negative. The project cannot be economically feasible at the listed tariffs. Different tariff rates have been assumed for the economic model, and it was found that at INR 8.50 ($0.13), Scenario 1 is attractive from economic point of view, and at INR 9 ($0.14) Scenario 1 and Scenario 2 are both economically viable with IRRs of 22% and 15%, respectively. Since the tariffs mentioned by CERC for different states are for a megawatt scale plant, the values are lower than the assumed value used in this study. If the state government increases the tariff by approximately INR 1.50 – 2.50 ($0.02-0.03) in the form of a subsidy relative to the values listed in Table 3, then small scale projects can become economically attractive. The increase in tariff would be in form of subsidy from the central and/or state government. Although this subsidy would be a burden on the relevant granting government agency, the positive externalities (boost in local economy, greenhouse gas reduction, etc.) associated may offset this cost.

The measures of the economic feasibility of the biomass gasifier for power generation are the levelized cost of electricity (LCOE) and the internal rate of return (IRR). At the assumed electricity price of INR 9.00 ($0.14/kWh), an IRR of 22% and a positive net present value are achieved in Scenario 1 (with subsidy), which is quite encouraging for such types of projects. Even in Scenario 2, the IRR value is 15% with a positive net present value if a rate of INR 9.00 per kWh ($0.14/kWh) is received for the power purchase agreement electricity price.

The LCOE depends on a number of factors such as the cost of biomass, operation and maintenance costs, capital costs, the amount of energy generated, etc. Since the delivered cost of rice straw heavily draws upon the collection efficiency of the straw combine, a graph has been plotted for LCOE versus collection efficiency. Figure 9 summarizes the range of collection efficiency values that are possible for the straw combine. It has been found through the economic model that in both the scenarios for every 10% increases in efficiency (keeping the baseline at 60%), there is a sharp decrease (almost INR 0.50 per kWh) in LCOE. Therefore, technologically advanced straw combines may be useful in lowering the LCOE.

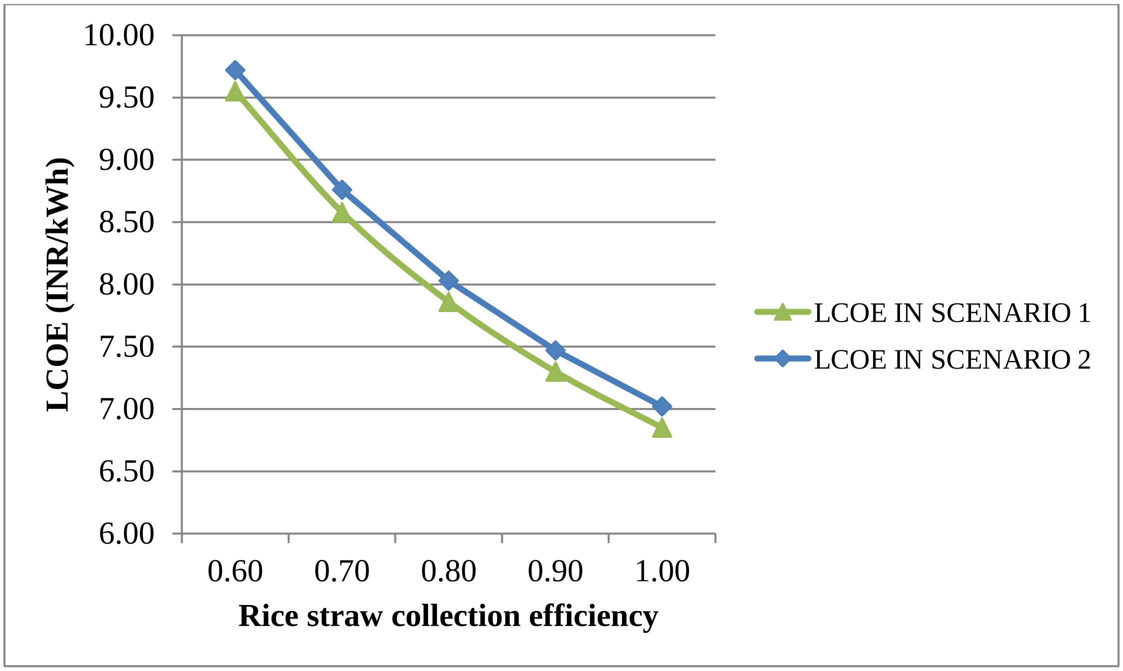

Figure 9. LCOE of generated electricity vs. straw collection efficiency for the straw combine.

Further, since the LCOE also depends on the cost of biomass, a graph (Figure 10) has been plotted to measure the degree of variation in the LCOE with changes in the cost of rice straw. The graph shows an almost linear relationship between the variables in both scenarios. For every increase of INR 0.10 per kg, there is increase of INR 0.23 per kWh in the LCOE. Therefore, reducing the delivered cost of rice straw is very important for lowering the LCOE of energy generated by such a project. The fact that multiple factors are involved does not, on its own, make it challenging to reduce the cost of rice straw collection.

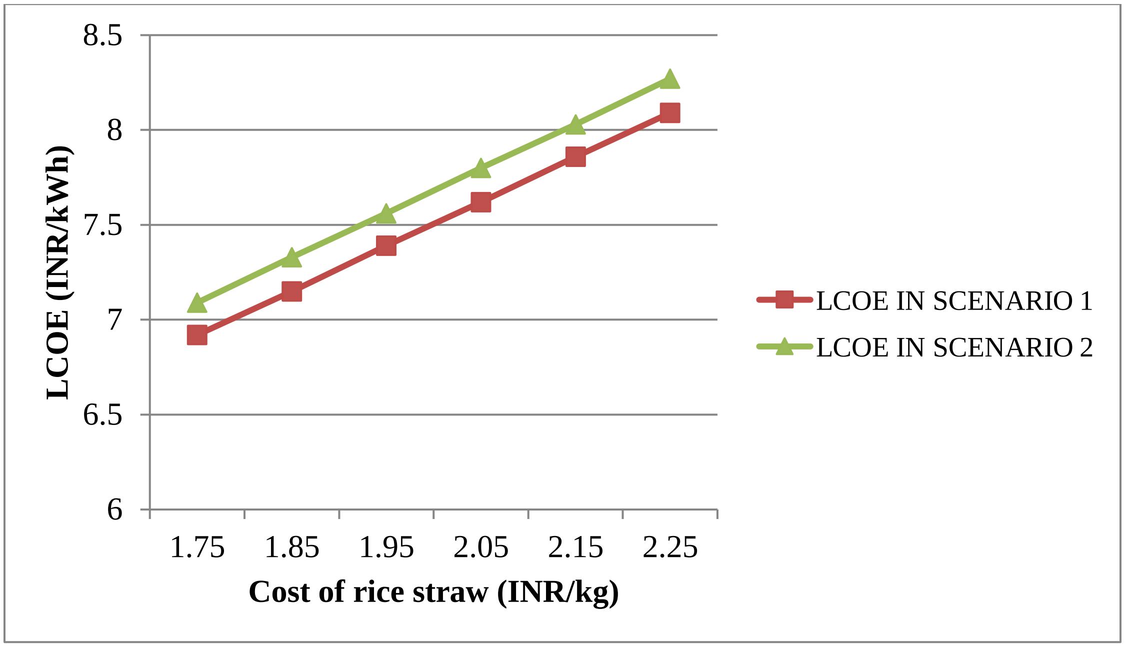

Figure 10. LCOE of generated electricity vs the cost of delivered rice straw

The capital cost plays an important role in estimating the impact on the value of the levelized cost of energy. In this research paper, it has been assumed that the cost of a 250-kW gasification-based power plant (INR 13,750,000, $211,962) is one-fourth of the cost of a 1 MW gasification-based power plant (INR 55,000,000, $847,849). A sensitivity analysis was conducted to observe the variation in the LCOE due to changes in the capital cost of a plant based on economies of scale. It can be seen in Figure 11 that as the capital cost of a plant increases by INR 2,500,000 ($38,538), i.e., by ~13%, the LCOE for Scenarios 1 and 2 also increases by INR 0.45/kWh (i.e., by 5%). This actually represents a sharp increase. A power purchase agreement must increase proportionally to the capital cost to maintain economic feasibility. If the capital cost increases more than INR 21,250,000 then the capital subsidy, which is fixed amount, makes trivial impact on the net difference of LCOE and eventually difference in LCOE in both the scenarios becomes negligible. Further, if the capital cost increases by 13% then the system becomes economically unviable at PPA of INR 9 in both the scenarios.

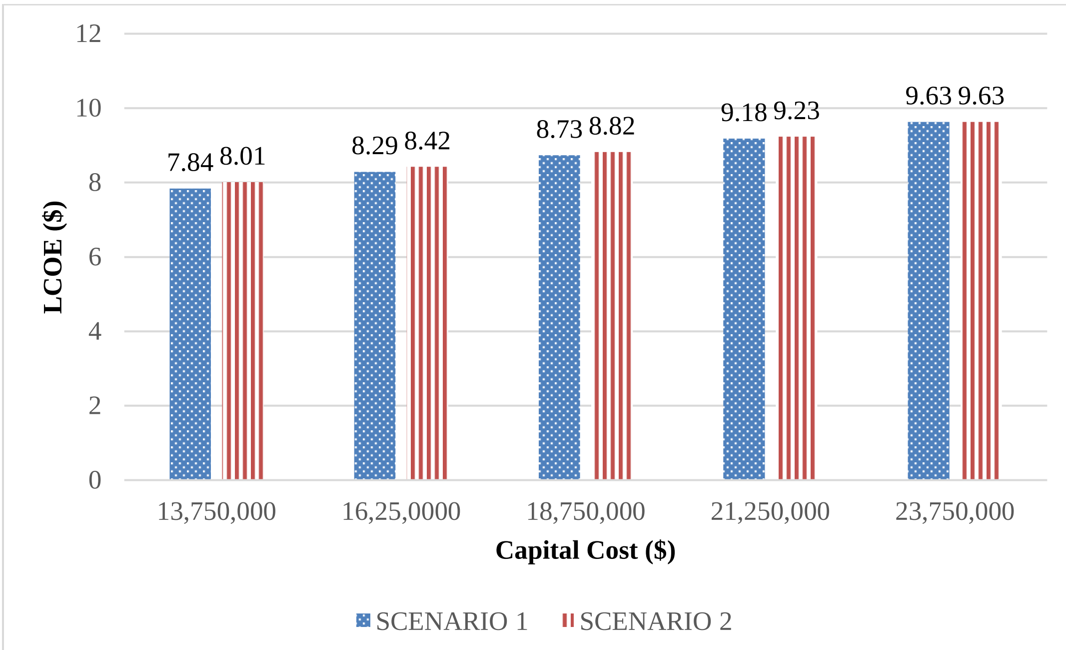

Figure 11 LCOE vs variation in project cost

Similarly, a graph (Figure 12) has been plotted to see the impact of O&M cost on the LCOE. Since INR 0.75 per kWh has been assumed for the O&M cost, the cost of operation and maintenance has been varied to determine the magnitude of change in LCOE. The outcome is that a change of INR 0.10 per kWh in O&M costs leads to a similar magnitude of change in the LCOE. Although O&M costs cannot be reduced significantly because of the fixed cost of labor and repair involved, timely maintenance and better man management can be used to reduce the cost of O&M. Another way to reduce the O&M cost per kWh is to increase the number of kWh generated. This might be the easiest strategy to achieve significant gains (i.e. increase the capacity factor of the system).

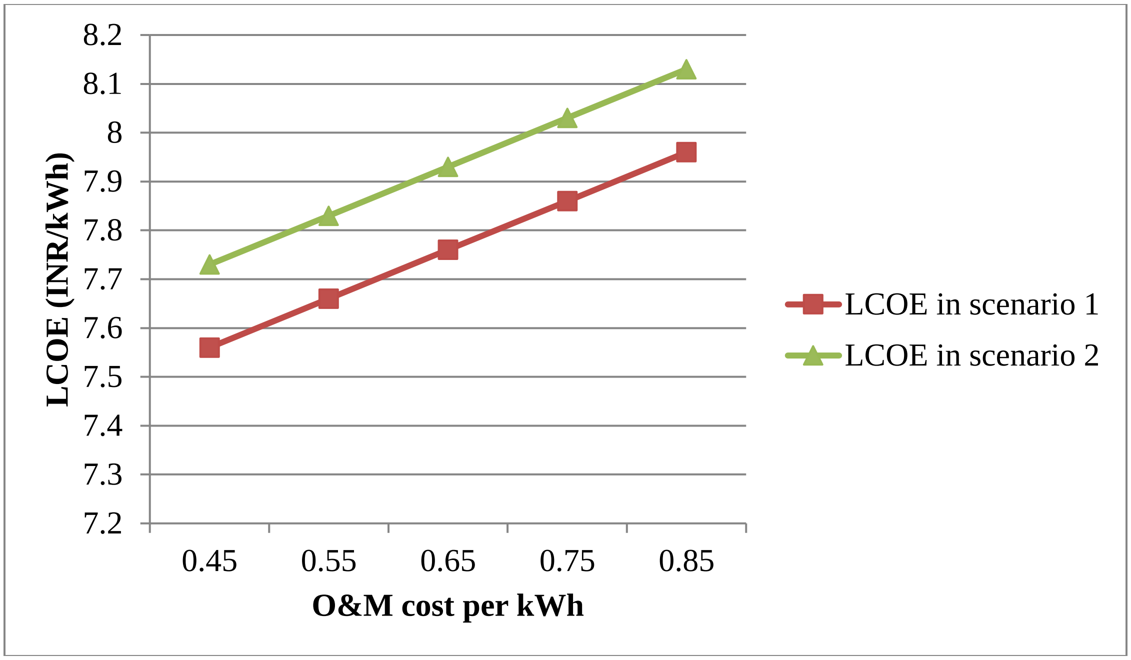

Figure 12. LCOE of generated electricity vs the O&M cost per kWh.

Regarding Topic 3, open field burning releases GHG gases including CO_2, N_2O, and CH_4. Since emission of CO_2 is nothing but giving back the absorbed CO_2 during the lifecycle of plant to the environment, only N_2O and CH_4 emissions have been considered for estimation of GHG emission. The annual emissions of GHGs (N_2O and CH_4) due to open field burning of rice straw has been calculated, and it was found that the total yearly emissions for India are 514,000 tCO_2e. Since biomass gasification is a carbon neutral process if the feedstock is a waste product, it can be effective in mitigating greenhouse gas emissions such as CH_4 and N_2O, and other harmful pollutants generated from open field burning. If the rice straw subjected to burning is utilized in gasification based power plant, then this emission could be avoided. However, the quantity of the rice straw is so huge that around 15,000 gasification plants (250kW) are required to utilize the whole quantity.

Further, the CO_2 emissions from open field burning of a given quantity of rice straw are not different from the CO_2 emissions from use of that same rice straw in a gasifier. The rice straw is converted into CO_2 either way. The primary savings in GHG emissions from gasification relative to open field burning are related to differences in CH_4 and N_2O emissions between the two processes. The proposed 250kW gasification plant can generate 767,250 kWh of electricity in a year if it runs for 12 hours daily for 341 days per year. Therefore, if the same amount of electricity is fed into grid replacing electricity from the national grid mix, the avoided annual GHG emissions would total 605 tCO_2e.

CONCLUSION AND OVERVIEW

India's power production capacity is predominantly coal-based. Given the threat of climate change and the recent ratification of the Paris Climate Accord by India, agricultural residue-based electrification technology can potentially meet India's electrification objectives. Power availability for villages in India is often ignored or kept at a lower priority during peak demand periods because revenue generation from the industrial or urban areas is given higher priority. Use of rice straw gasification technology not only strengthens the power generation capacity and reduces greenhouse gas emissions; it can also improve the rural economy and support the sustainable development goals of India. This paper investigates the technical and economic aspects of off-grid and grid-connected small scale electricity generation using rice straw gasification technology in India.

The delivered cost of rice straw transported 10 km to the power plant has been estimated at INR 2.05 (USD 0.03) per kg. Exploration of various technological options revealed that a gasifier with an internal combustion engine designed to operate on 100% producer gas is a suitable option for installing a 250-kW grid connected power plant.

The economic analysis in this research paper reveals that while the system is not feasible at current power purchase agreement (PPA) prices of INR6.50 to INR7.50 per kWh ($0.10-0.11/kWh) in India for biomass gasification based power plants; it is feasible at prices more than INR 9.00 ($0.14/kWh). At an assumed power purchase price of electricity of INR 9.00 per kWh ($0.14/kWh), the results give an IRR of 22% and LCOE

$0.12/kWh (Scenario 1, with MNRE capital subsidy) and IRR 15% and $0.12/kWh (Scenario 2, without capital subsidy), with positive net present value of the 10-year lifetime both scenarios. However, capital costs higher than the assumed value can lower the IRR value significantly and would likely make the system economically unviable.

Further, agricultural residue gasification-based generation helps to reduce CO_2e emissions generated from the open field burning. It is estimated in this research paper that replacing electricity from prevailing grid mix in India with 250 kW gasification based power plant can avoid 605 tCO_2e. Thus, biomass-based gasification helps to mitigate greenhouse gas emissions and related problems.

Agricultural residue gasification-based power generation is likely to create employment opportunities rural areas. These include the need for skilled and semi-skilled labor for collection and supply of rice straws and operation and maintenance of the gasifier plants. Rice straw gasification based power plants have employment and other potential benefits that have not been quantified and compared with other energy generation options. Further research might reveal whether or not the un-quantified benefits of rice straw gasification based power plants exceed the minimum feasible PPA. Consequently, more research is needed in area of rice straw gasification in India. Similar grid connected power plants in Karnataka, and decentralize power plants in West Bengal have been successfully implemented. A technological model for rice straw based system could be based on these caste studies.

The findings of this research can be utilized by policy makers and power utilities for policy recommendations/ briefs and business models, respectively, for the development of small scale rice straw based grid-connected power plant across rice producing states.

POLICY RECOMMENDATIONS

Based on this study, the following actions plan may be recommended to the Government of India, other policy makers, and private sector developers of biomass energy systems for enhancing the effective utilization of this energy resource.

1. More study is needed to evaluate true cost and benefits of such system. Gasifier technology should be encouraged by establishment of design guidelines, performance standards and testing & certification. Government-approved vendors should only be allowed to sell or setup the plant across county to ensure the quality of products.
2. The Ministry of Agriculture should encourage private companies to establish village-level custom hiring centers for farm machinery. This will ensure easy accessibility of customized hiring farm equipment to farmers.
3. Renewable energy supply companies should be encouraged to act as energy service companies, making these companies responsible for operation and maintenance of gasifiers while also working to improve community involvement and awareness for these systems. Direct purchase of fuel biomass from individual villagers will provide them with livelihood earning opportunities.
4. Regular information and awareness programs should be conducted to convince the rural population about the negative impact of open field burning.

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APPENDIX A: RICE AND RICE STRAW PRODUCTION IN INDIA

The data of annual production of rice in India is given in Table A.1. Paddy crops are biannual crops therefore the production data is given for two different seasons. Table A.2 is list of assumptions taken for estimating the average straw yield per hectare in India.

Table A.1. Quantity of rice produced in India from 2010 to 2015. Source ((Department of Agriculture, 2016)

Year	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	Total (mT)
Kharif (mT)	80.7	92.8	92.4	91.5	90.9	448.3
Rabi (mT)	15.3	12.5	12.9	15.2	13.9	69.8

Table A.2. List of assumptions required to calculate average straw yield per hectare and amount of rice straw subject to open field burning.

Assumptions	Values	References
Rough rice (Million Tons)	155.43	(Department of Agriculture, 2016)
Straw Grain Ratio	0.75	(Gadde, Bonnet, Menke, & Garivait, 2009)
Quantity of surplus rice straw (%)	0.23	(Narciso & Hossain, 2007)
Quantity if rice straw exposed to burning (million tons)	26.81	calculated by author
Average Rice Yield (ton/hectare)	2.30	(Government of India, 2017)
Average straw yield (kg/hectare)	2,588	calculated by author
Average straw collected (kg/hectare)	2,070	calculated by author
HHV of rice straw(MJ/kg)	15.3	(Jenkins, Baxter, Jr, & T.RMilesc, 1998)
Amount of rice straw required to generate one unit of energy (kg)	2.4	calculated by author
Energy potential of rice straw subject to burning every year (million kWh)	11,395	calculated by author

APPENDIX B: COST ASSUMPTIONS USED IN THE STUDY

Appendix B contains assumed cost of machinery, fuel, and cost assumption data and for economic analysis. Table B.1 shows the cost assumptions used in the study. These assumptions were key inputs in determining the delivered cost of rice straw for rice straw based power plant within 10 km of distance. Table B.2 shows the capital cost assumptions used in the study. These assumptions were key inputs in determining the levelized cost of energy of a gasifier-based 250 kW power plant.

Table B.1. Capital cost assumptions used in the study

Particulars	Price	Unit	References
Straw combine	1,500	INR Per hectare	(Bansal, 2017)
Fuel consumption	531	INR Per hectare	(Tractorsinfo, 2017)
Tractor cost	160	INR Per hour	(DFWAD, 2017)
Man power(unskilled)	513	INR Per day	(Government of Delhi, 2017)
Diesel requirement	3	Liter Per hour	(Tractorsinfo, 2017)
Loading capacity of 35 horse power tractor (kg)	1,200	kg	(Tractorsinfo, 2017)
Speed of tractor	30	km/hour	(Tractorsinfo, 2017)
Cost of diesel per liter	63.17	INR	December 2017 data
Tractor driver (skilled)	622	Per day	(Government of Delhi, 2017)

Table B.2. Economic Assumptions for economic feasibility of power plant

Particulars	Values	References
Capital cost of 250kW plant	₹ 13,750,000	(Sreevatsan, 2011)
Operation and Maintenance cost	₹ 575,437	(Sreevatsan, 2011)
No of days of operation in one year (day)	341	assumed by author
No of running hours in one day (hour)	12	assumed by author
Annual Rice Straw Consumption(kg)	1,805,294.12	calculated by author
Annual Cost of rice straw	₹ 3,883,259.68	calculated by author
Tariff /kWh	₹ 9.00	Assumed value
Power generation (kWe)	187.50	calculated by author using 25% derating of engine (Raman & Ram, 2013)
Bank Loan Scenario 1	₹ 9,625,000.00	calculated by author
Bank Loan@	11.50%	(IREDA, 2014).
Loan Term	10	(IREDA, 2014).
Bank Loan for scenario 2	₹ 9,625,000.00	calculated by author
Annual EMI Scenario 1	₹ 1,623,877.43	calculated by author
Annual EMI Scenario 2	₹ 1,623,877.43	calculated by author
Subsidy	₹ 3,750,000.00	(MNRE, 2011)
Discount Rate	10.7%	(CERC, 2016)

Table B.3. Nominal monthly payment against loan repayment in Scenario1.

Year	Month	Nominal Net Annual debt	Nominal monthly payment
0	1		₹ 135,323.12
	2		₹ 135,323.12
	3		₹ 135,323.12
	4		₹ 135,323.12
	5		₹ 135,323.12
	6		₹ 135,323.12
	7		₹ 135,323.12
	8		₹ 135,323.12
	9		₹ 135,323.12
	10		₹ 135,323.12
	11		₹ 135,323.12
1	12	₹ 1,623,877.43	₹ 135,323.12
	13		₹ 111,760.73
	14		₹ 111,760.73
	15		₹ 111,760.73
	16		₹ 111,760.73
	17		₹ 111,760.73
	18		₹ 111,760.73
	19		₹ 111,760.73
	20		₹ 111,760.73
	21		₹ 111,760.73
	22		₹ 111,760.73
	23		₹ 111,760.73
2	24	₹ 1,341,128.72	₹ 111,760.73
	25		₹ 111,760.73
	26		₹ 111,760.73
	27		₹ 111,760.73
	28		₹ 111,760.73
	29		₹ 111,760.73
	30		₹ 111,760.73
	31		₹ 111,760.73
	32		₹ 111,760.73
	33		₹ 111,760.73
	34		₹ 111,760.73

Year	Month	Nominal Net Annual debt	Nominal monthly payment
	35		₹ 111,760.73
3	36	₹ 1,341,128.72	₹ 111,760.73
	37		₹ 111,760.73
	38		₹ 111,760.73
	39		₹ 111,760.73
	40		₹ 111,760.73
	41		₹ 111,760.73
	42		₹ 111,760.73
	43		₹ 111,760.73
	44		₹ 111,760.73
	45		₹ 111,760.73
	46		₹ 111,760.73
	47		₹ 111,760.73
4	48	₹ 1,341,128.72	₹ 111,760.73
	49		₹ 111,760.73
	50		₹ 111,760.73
	51		₹ 111,760.73
	52		₹ 111,760.73
	53		₹ 111,760.73
	54		₹ 111,760.73
	55		₹ 111,760.73
	56		₹ 111,760.73
	57		₹ 111,760.73
	58		₹ 111,760.73
	59		₹ 111,760.73
5	60	₹ 1,341,128.72	₹ 111,760.73
	61		₹ 111,760.73
	62		₹ 111,760.73
	63		₹ 111,760.73
	64		₹ 111,760.73
	65		₹ 111,760.73
	66		₹ 111,760.73
	67		₹ 111,760.73
	68		₹ 111,760.73

Year	Month	Nominal Net Annual debt	Nominal monthly payment
	69		₹ 111,760.73
	70		₹ 111,760.73
	71		₹ 111,760.73
6	72	₹ 1,341,128.72	₹ 111,760.73
	73		₹ 111,760.73
	74		₹ 111,760.73
	75		₹ 111,760.73
	76		₹ 111,760.73
	77		₹ 111,760.73
	78		₹ 111,760.73
	79		₹ 111,760.73
	80		₹ 111,760.73
	81		₹ 111,760.73
	82		₹ 111,760.73
	83		₹ 111,760.73
7	84	₹ 1,341,128.72	₹ 111,760.73
	85		₹ 111,760.73
	86		₹ 111,760.73
	87		₹ 111,760.73
	88		₹ 111,760.73
	89		₹ 111,760.73
	90		₹ 111,760.73
	91		₹ 111,760.73
	92		₹ 111,760.73
	93		₹ 111,760.73
	94		₹ 111,760.73
	95		₹ 111,760.73
8	96	₹ 1,341,128.72	₹ 111,760.73
	97		₹ 111,760.73
	98		₹ 111,760.73
	99		₹ 111,760.73
	100		₹ 111,760.73
	101		₹ 111,760.73
	102		₹ 111,760.73

Year	Month	Nominal Net Annual debt	Nominal monthly payment
	103		₹ 111,760.73
	104		₹ 111,760.73
	105		₹ 111,760.73
	106		₹ 111,760.73
	107		₹ 111,760.73
9	108	₹ 1,341,128.72	₹ 111,760.73
	109		₹ 111,760.73
	110		₹ 111,760.73
	111		₹ 111,760.73
	112		₹ 111,760.73
	113		₹ 111,760.73
	114		₹ 111,760.73
	115		₹ 111,760.73
	116		₹ 111,760.73
	117		₹ 111,760.73
	118		₹ 111,760.73
	119		₹ 111,760.73
10	120	₹ 1,341,128.72	₹ 111,760.73

Table B.4. Nominal monthly payment for loan repayment in Scenario 2

Year	Month	Nominal Net Annual debt	Nominal monthly payment
0	1		₹ 135,323.12
	2		₹ 135,323.12
	3		₹ 135,323.12
	4		₹ 135,323.12
	5		₹ 135,323.12
	6		₹ 135,323.12
	7		₹ 135,323.12
	8		₹ 135,323.12
	9		₹ 135,323.12
	10		₹ 135,323.12
	11		₹ 135,323.12
1	12	₹ 1,623,877.43	₹ 135,323.12
	13		₹ 135,323.12
	14		₹ 135,323.12
	15		₹ 135,323.12
	16		₹ 135,323.12
	17		₹ 135,323.12
	18		₹ 135,323.12
	19		₹ 135,323.12
	20		₹ 135,323.12
	21		₹ 135,323.12
	22		₹ 135,323.12
	23		₹ 135,323.12
2	24	₹ 1,623,877.43	₹ 135,323.12
	25		₹ 135,323.12
	26		₹ 135,323.12
	27		₹ 135,323.12
	28		₹ 135,323.12
	29		₹ 135,323.12
	30		₹ 135,323.12
	31		₹ 135,323.12
	32		₹ 135,323.12
	33		₹ 135,323.12
	34		₹ 135,323.12

Year	Month	Nominal Net Annual debt	Nominal monthly payment
	35		₹ 135,323.12
3	36	₹ 1,623,877.43	₹ 135,323.12
	37		₹ 135,323.12
	38		₹ 135,323.12
	39		₹ 135,323.12
	40		₹ 135,323.12
	41		₹ 135,323.12
	42		₹ 135,323.12
	43		₹ 135,323.12
	44		₹ 135,323.12
	45		₹ 135,323.12
	46		₹ 135,323.12
	47		₹ 135,323.12
4	48	₹ 1,623,877.43	₹ 135,323.12
	49		₹ 135,323.12
	50		₹ 135,323.12
	51		₹ 135,323.12
	52		₹ 135,323.12
	53		₹ 135,323.12
	54		₹ 135,323.12
	55		₹ 135,323.12
	56		₹ 135,323.12
	57		₹ 135,323.12
	58		₹ 135,323.12
	59		₹ 135,323.12
5	60	₹ 1,623,877.43	₹ 135,323.12
	61		₹ 135,323.12
	62		₹ 135,323.12
	63		₹ 135,323.12
	64		₹ 135,323.12
	65		₹ 135,323.12
	66		₹ 135,323.12
	67		₹ 135,323.12
	68		₹ 135,323.12

Year	Month	Nominal Net Annual debt	Nominal monthly payment
	69		₹ 135,323.12
	70		₹ 135,323.12
	71		₹ 135,323.12
6	72	₹ 1,623,877.43	₹ 135,323.12
	73		₹ 135,323.12
	74		₹ 135,323.12
	75		₹ 135,323.12
	76		₹ 135,323.12
	77		₹ 135,323.12
	78		₹ 135,323.12
	79		₹ 135,323.12
	80		₹ 135,323.12
	81		₹ 135,323.12
	82		₹ 135,323.12
	83		₹ 135,323.12
7	84	₹ 1,623,877.43	₹ 135,323.12
	85		₹ 135,323.12
	86		₹ 135,323.12
	87		₹ 135,323.12
	88		₹ 135,323.12
	89		₹ 135,323.12
	90		₹ 135,323.12
	91		₹ 135,323.12
	92		₹ 135,323.12
	93		₹ 135,323.12
	94		₹ 135,323.12
	95		₹ 135,323.12
8	96	₹ 1,623,877.43	₹ 135,323.12
	97		₹ 135,323.12
	98		₹ 135,323.12
	99		₹ 135,323.12
	100		₹ 135,323.12
	101		₹ 135,323.12
	102		₹ 135,323.12

Year	Month	Nominal Net Annual debt	Nominal monthly payment
	103		₹ 135,323.12
	104		₹ 135,323.12
	105		₹ 135,323.12
	106		₹ 135,323.12
	107		₹ 135,323.12
9	108	₹ 1,623,877.43	₹ 135,323.12
	109		₹ 135,323.12
	110		₹ 135,323.12
	111		₹ 135,323.12
	112		₹ 135,323.12
	113		₹ 135,323.12
	114		₹ 135,323.12
	115		₹ 135,323.12
	116		₹ 135,323.12
	117		₹ 135,323.12
	118		₹ 135,323.12
	119		₹ 135,323.12
10	120	₹ 1,623,877.43	₹ 135,323.12

APPENDIX C: MODEL USED IN THE STUDY FOR GHG CALCULATION

Appendix C contains Table C.1, which contains a listing of emission factors of different greenhouse gases and average annual CO_2e emission caused by open field burning in India.

Table C.1. Estimated annual greenhouse gas emission due to open field burning in India Source: (EPA, 2014).

	Quantity of rice straw burnt yearly (ton)	CH_4 emission factor (g/kg)	GWP of CH_4	CH_4 emission(t)	N_2O emission factor	GWP of N_2O	N_2O emission (ton)	Total CO_2e (ton)
Open field burning of rice straw	26,811,675	0.29	25	194,000	0.04	298	390,000	514,000