MODELLING AND OPTIMIZATION OF BIOMASS BASED SYSTEM IN MICROGRID

A Thesis

submitted in fulfilment of the requirements for the award of the degree of

Doctor of Philosophy

in Engineering

Submitted by

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June, 2022

CERTIFICATE

This is to certify that the thesis entitled **"Modelling and Optimization of Biomass Based System in Microgrid"** being submitted by Mr. Arashdeeep Singh to the Department of Electrical & Instrumentation Engineering, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala, Punjab, India for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by him under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard.

The results embodied in the thesis have not been submitted in part or full to any other Institute or University for the award of any diploma or degree.

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ACKNOWLEDGEMENTS

I would like to extend thanks and gratitude to the many people, who so generously contributed to the work presented in this thesis. I honestly feel short of words to acknowledge all those who helped me directly and indirectly during this research work.

With due regards and great delight, I convey my heartful gratitude and indebtedness to my supervisor **Dr. Prasenjit Basak**, Associate Professor, Department of Electrical & Instrumentation Engineering, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala for skilful guidance, persistent encouragement, proficient evaluation and conscientious supervision throughout this academic endeavour. He was always available to help me with utmost care, kind attention and prudent suggestions during odd hours of the job. His hard working nature and methodical suggestions were a constant source of encouragement to me. It is owing to his guidance, expertise, inquisitive attitude and tireless efforts apart from his working hours that I find my vision even more broadened. I earnestly thank him from the core of my heart for being a consistent source of inspiration right through the beginning till the end.

I am very thankful to **Dr. Parag Nijhawan**, Associate Professor, Department of Electrical & Instrumentation Engineering, **Dr. Sanjeev Kumar Aggarwal**, Associate Professor, Department of Electrical & Instrumentation Engineering and **Dr. Kulbir Singh**, Professor, Department of Electronics & Communication Engineering, for being the member of Doctoral Committee and spending their valuable time in reviewing and critically examining the work. I am also very grateful to **Dr. Mandeep Singh**, Professor & Ph.D. coordinator, Department of Electrical & Instrumentation Engineering for his kind suggestions.

I am also thankful to present Chairman of the Doctoral Committee **Dr. R. S. Kaler**, Senior Professor & Head, Department of Electrical & Instrumentation Engineering for the much needed support throughout the work.

My heartfelt gratitude is due to **Dr. Rafat Siddique**, Senior Professor & Dean, Research and Sponsored Projects and Honourable Director **Dr. Prakash Gopalan** for the support, encouragement and providing the necessary facilities to carry out and complete this work on steady course.

I also wish to express my deep sense of gratitude to all the faculty and staff members, particularly **Dr. Souvik Ganguli**, Assistant Professor of the Department of Electrical & Instrumentation Engineering, **Dr. Shakti Singh**, Assistant Professor of the Department of Electrical & Instrumentation Engineering and all the persons who with their encouraging and caring words, constructive criticism and suggestions have contributed directly or indirectly in a significant way towards completion of this research work. My deepest appreciations are due to the research scholars under the supervision of **Dr. Prasenjit Basak**. They have always stood by me in all difficult times and reinforced my confidence. Their never ending support is a constant source of motivation and always keeps me going.

I bow with gratitude for my family members who are the most precious persons in my life and without their efforts I would have not achieved this milestone.

I express my gratitude to all those, with whom I have worked, interacted and whose thoughts have helped me in furthering my grasps and understanding of the work.

Last but not the least, I bow in reverence to **ALMIGHTY GOD** who has always showered blessings on me at each and every step to complete this thesis.

Arashdeep Singh

Abstract

The handling of biomass like MSW and rice straw becomes a challenge in the present time due to various economic and environmental challenges. Finding an economical and environmentally sustainable MSW and rice straw processing system is necessary. For hybrid power generation systems, biomass can act as a balancing system to wind and solar resources due to its different properties related to reliability. The utilization of MSW and rice straw in a microgrid system will open new doors for its sustainable processing and energy generation. This study proposes modelling and simulation of MSW and rice straw-based microgrids along with their economic and environmental evaluation. The technologies are selected after a comparative analysis of various technologies in economic and environmental terms for a particular type of biomass (MSW and rice straw).

The characteristic assessment and comparative analysis of various municipal solid waste (MSW) and rice straw processing technologies are proposed to fulfill this aim. In the case of MSW, landfilling is taken as the common way to handle MSW. In contrast, the technologies such as anaerobic digestion (AD), compost, refuses derived fuel (RDF), incineration, and gasification are selected as the alternate systems to process MSW. Along with the electricity generation technologies (AD, Gasification, and incineration), other technologies such as RDF and composting are selected to compare and find the most sustainable means to process the MSW. Considering the virtual operation of the existing plants, the techno-economic and environmental parameters of all the selected technologies are assessed in the Indian scenario. For evaluation of each system, the industrial ecology-based symbiotic system approach along with Life cycle assesement (LCA) is applied to Indian MSW taking a population size of one million. All the selected technologies are evaluated in detail at each step of the whole process and compared with each other in economic and environmental terms. In a similar approach, the characteristic assessment and comparative analysis of various rice straw processing technologies are also proposed. The same methodology is applied to evaluate rice straw processing techniques using incineration, gasification, AD, fermentation, and integrated operation of fermentation and AD.

Then selecting the best techniques, modelling, and simulation of MSW and rice straw-based microgrids are proposed. In case of MSW the proposed microgrid is capable of processing the urban waste of a small city of 0.1 million population and fulfilling the electricity demand of a nearby village having 225 houses. The proposed microgrid consists of MSW processing techniques: AD (processes a wet portion of MSW) and gasification (processes a dry portion of MSW) that are further integrated with solar,

battery, and the main grid. After selecting the gasification technique, modelling and simulation of a small-scale rice straw-based microgrid is proposed. This microgrid is capable to process the surplus rice straw of a village having 250 houses and 900 acres of cultivated land. The system processes 1128 tonne/year of surplus rice straw and meets the load demand of the same village. The gasification technique that processes rice straw to produce electricity is further integrated with solar, battery, and the utility grid. The modelling and simulation of both the systems are done using Matlab software. The size of the microgrids is optimized using an artificial bee colony (ABC) algorithm. The effectiveness of the adopted technique is verified by comparing the results with the particle swarm optimization (PSO) algorithm. The economic evaluation of the proposed systems is done based on net present cost (NPC), annualized system cost (ASC), and the levelized cost of electricity (LCOE). The landfill avoided cost is also calculated along with the waste processing cost. The environmental impact of the proposed microgrids is also evaluated using the LCA methodology.

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LIST OF ACRONYMS, SYMBOLS AND ABRIVATIONS

ABC	Artificial Bee Colony
AC	Alternating Current
AD	Anaerobic Digestion
AP	Acidification Potential
ASC	Annualized System Cost
A_{pv}	Alternative Potential Value (INR)
A_{TCt}	Total Alternative Cost of Processing (INR/Tonne)
A_{PVt}	Alternative Potential Value (INR/Tonne)
Ah	Ampere Hour
BOD	Bio-Chemical Oxygen Demand
$B_{bg}(t)$	Biomass (Tonne)
B_{pp}	Biogas Production Potential (m^3/tonne)
B_{bmg}	Biomass Available (tonne/day)
C_2H_4	Ethene
CCHP	Combined Cooling, Heating, and Power
CERC	Central Electricity Regulatory Commission
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
COE	Cost of Electricity
CPCB	Central Pollution Control Board
C-rate	Current Rate
CRF	Capacity Recovery Factor
CrPC	Criminal Procedure Code
CUF	Capacity Utilization Factor
CV	Calorific Value
C_{av}	Total Avoided Cost (INR)

C_{avt}	Transport Avoided Cost (INR)
C_{avl}	Landfill Avoided Cost (INR)
C_t	Transportation Cost (INR)
C_{sg}	Segregation Cot (INR)
C_{pt}	Pre-Treatment Cost (INR)
C_{sh}	Shredding Cost (INR)
C_c	Converting Cost (INR)
C_{op}	Operating Cost (INR)
C_{ma}	Maintaince Cost (INR)
C_{cap}	Capital Cost (INR)
C_{rt}	Residue Transportation (INR)
C_{rl}	Landfill Cost (INR)
C_r	Residue Cost (INR)
C_{at}	Alternative Total Cost (INR)
C_f	Feedstock Cost (INR)
C_c	Converting Cost (INR)
C_{Ct}	Plant Capital Cost (INR)/Tonne
CV_{bmg}	Calorific Value of Dry Waste (MJ/kg)
C_f	Cost of Feedstock (INR)
C_b(ah)	Single Battery capacity (Ah)
DC	Direct Current
DERs	Distributed Energy Resources
EP	Eutrophication Potential
EPA	Environment Protection Agency
eq.	Equivalent
F_{Ct}	Cost of Feedstock (INR/Tonne)
F_{loss}	The loss factor
F_d	Feedstock Processed (Tonne/Day)
GHG	Greenhouse Gas
GJ	Gigajoules
GWP	Global Warming Potential

Gh(t)	Solar Radiation (W/m^2) at any time (t)
Gs	Standard Solar Incident Radiation (W/m^2)
H_2S	Hydrogen Sulphide
HCL	Hydrogen Chloride
HF	Hydrogen Fluoride
INR	Indian Rupees
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kcal	Kilocalorie
kg	Kilogram
km	Kilo Meter
kWh	Kilowatt Hour
L	Litre
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LFG	Landfill Gas
LHV	Lower Heating Value
Mha	Mega Hectare
MJ	Megajoules
MNRE	Ministry of New and Renewable Energy Resources
MSW	Municipal Solid Waste
OM_{CY}	Operating and Maintenance Cost of Plant(INR/Year)
OM_{Ct}	Operating and Maintenance Cost (INR)/Tonne
N	Nitrogen
N m^3	Normal Cubic Meter
N_2	Dinitrogen
N_2O	Nitrogen Oxide
NH_3	Ammonia
NIIST	National Institute for Interdisciplinary Science and Technology
NO_X	Nitrogen Oxide
NPC	Net Present Cost

NSSO	National Sample Survey Organization
η_{inv}	Efficiency of Inverter
η_{bio}	Conversion Efficiency (from biogas to electricity)
η_{rec}	Efficiency of the Rectifier
N_{sol_max}	Maximum Number of PV Panels
N_{sol_max}	Maximum Number of Batteries
η_{bat}	Battery's Round Trip Efficiency
η_{bat_c}	Battery's Charging Efficiency
η_{bio_d}	Battery's Discharging Efficiency
N_{bat}	Total Number of Batteries
N_{sol}	Total Number of PV Panels
PM	Particulate Matter
PO_4	Phosphate Ion
POCP	Photochemical Oxidants Creation Potential
PSO	Particle Swarm Optimization
PV	Photovoltaic
$P_{ld}(t)$	Peak Load Demand (kWh)
$P_{inv}(t)$	Power Rating of Inverter (kW)
P_v	Product Value (INR)
$P_{Gs}(t)$	Power Sold to Grid (kWh)
$P_{Gp}(t)$	Power Purchased from Grid (kWh)
$P_{b\_min}(t)$	Minimum Power Capacity of Battery Bank (kWh)
$P_{bio}(t)$	Output of Biogas system (kWh/hour)
P_{bio_max}	Maximum Installed Capacity of AD Plant (kW)
P_{gasi_max}	Maximum Installed Capacity of Gasifier System (kW)
P_{sol}	Power Output of a PV System (kW)
P_r	Power Rating of Single PV Panel (kW)
$P_b(t)$	Battery Output/Input Power (kWh)
$Q(t)$	Biogas Production (m^3/hour)
RDF	Refused Derived Fuel
RED	Renewable Energy Directive

SO_2	Sulphur Dioxide
SOC	State of Charge
SOC_{min}	Minimum State of Charge
SOC_{min}	Maximum State of Charge
tpd	Tonne Per Day
USD	United States Dollar
UT	Union Territories
VOC	Volatile Organic Compound
V_{bus}	Bus Voltage (V)
V_{bat}	Voltage of a Particular Battery (V)

CHAPTER 1

Introduction and literature survey

1.1 Background: The microgrid

Currently, the electricity demand is increasing, and the power system network needs improved energy utilization efficiency and reliability. In this changing scenario, the new renewable energy-based power generation techniques with fewer carbon footprints will be implemented [1]. The microgrid is one of the sound local power supply systems that consists of distributed generators, loads, power storage devices, and heat recovery equipment [2]. It helps reduce the congestion cost by reducing network congestion, line losses, and line costs, thereby increasing energy efficiency [3]. The choice of distributed energy resources (DERs) for microgrids depends on various parameters, including geographical conditions of the site, the climate and topology of the region, and fuel availability. The DER technologies like combined heat and power (CHP) systems, Wind energy conversion system, solar photovoltaic (PV) systems, Small-scale hydroelectric generation and storage devices can provide sustainable energy services [4]. According to the geographical location of India, most of the population is dependent upon an agricultural economy resulting in abundant biomass. Due to India's high population, considerable urban waste is also generated every year. This biomass can be burned or digested to produce energy using advanced technologies such as anaerobic digestion (AD) [5] and gasification [6]. Biomass is a resource with versatile utility [7]; it can be used to produce electricity as one of the DERs in microgrid systems, improving its reliability by reducing the uncertainty present in solar and wind power generation technologies. A typical microgrid model is shown in Figure 1.1 consists of solar, wind, biomass, and energy storage system.

1.2 Motivation for research

Increasing energy demand and depletion of fossil fuels make it necessary to increase reliance on renewable energy resources [8]. In the last two decades, solar and wind power generation technologies have become popular due to their environmental benefits, but both the technologies

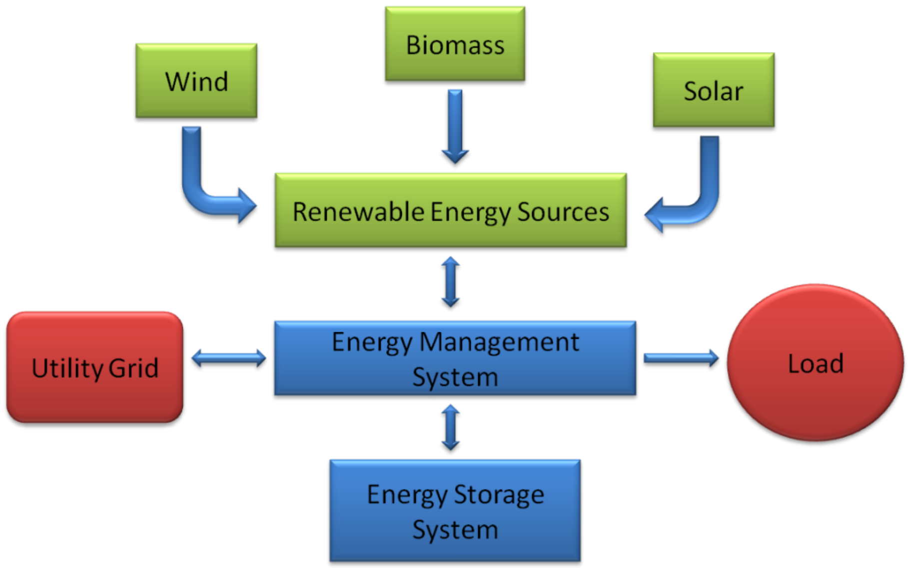

Figure 1.1: Model of Microgrid

have their limitation related to reliability due to their stochastic nature [9]. Presently, biomass like a municipal solid waste (MSW) and agricultural waste are drawing attention because both have good power potential [10]. The conventional methods to handle these wastes are not environment friendly. Due to the massive increase in population, the waste management system has become a challenge in developing countries like India [11]. This country generates 55 million tonne of MSW annually with an escalation rate of 5% per annum, and up to 2047, it is estimated to reach 300 million tonne per year [12]. Open dumping is the most common way in India to dispose of urban waste. The status of 90% of dump sites has been found unacceptable due to over-dumping [13]. From the total estimated power potential of MSW (1700 MW), merely 2% is utilized, and in the total power generating capacity of India, coal has a significant share of 69% [14]. The Ministry of Environment, Forests, and Climate Change recently notified the new Solid Waste Management Rules (SWM), 2016 [14], to improve the present waste management scenario. The salient features of this rule are (i) Every citizen shall segregate waste and store separately and hand over to municipal workers. (ii) In order to monitor and review Ministry of Environment, Forest & Climate Change shall constitute 'Central Monitoring Committee'. (iii) There is a need to frame national policy on waste management with the coordination of states/UTs and must provide technical guidelines, financial support, training to local bodies. (iv) The departments of fertilizers and chemicals will help in market development regarding city compost and the procurement of the same to the companies. (v) The flexible fertilizers control order will be generated by the Ministry of Agriculture to promote compost, generate testing facilities for compost, and lay down guidelines. (vi) Ministry of Power shall fix the power generation tariffs from waste to energy plants, and it will ensure the distribution of the power through these companies. MNRE will be responsible for the infrastructure of waste-to-energy plants and grant subsidies.

The increasing population causes hasty urbanization, industrialization, and economic growth, increasing waste generation globally [15]. The world has a total population of 7.7 billion (approximately), increasing enormously with an escalation rate of 2% per annum. The MSW generation per day is estimated to become double in 2025 (6.1 million tonne) in comparison to 2002 (3.5 million tonne) [16].

India has a large wasteland area of 46.67 Mha, out of which about 39.24 Mha can be utilized to produce biomass for energy generation [17]. India has 1.79 Mkm^2 of cultivated land, 60.5% of the total land area. With a cropping intensity of about 140% [18], approximately 180 Mha area is under agricultural cultivation. About 611 million tonne residues are produced annually, and 158 million tonne are estimated as surplus [19]. The primary surplus residues are sugarcane bagasse (41 million tonne/year), paddy straw (28 million tonne/year), wheat straw (21 million tonne /year), and cotton stalks (19 million tonne /year) [20]. Open burning is the common practice in India to dispose of surplus straw. The Indian state of Punjab has only 1.5% of the total country's cultivable area, from which it produces 55% of the country’s rice, 25% of cotton, and 22% of wheat [21]. It produces 10.88 million tonne of rice annually with a straw yield of 1.5 times the rice production [22]. In Punjab, the primary surplus crop residue available is rice and wheat straw which contribute 74.81% of the total agricultural residue. It can be utilized to meet 15% of the total energy demand. There were reports [18] that show that there is 48% availability factor for rice straw in Punjab and Haryana. In India, 23% of rice straw is surplus that is not being appropriately utilized; it is either left or primarily burned in the fields. In Punjab, 83.5% of the surplus rice straw is available [20].

The burning of paddy straw continues unabated in Punjab [23], which leads to an increase in particulate matter in the air [24]. Also, oil dust particles cause health problems like nose, throat, lungs, and heart problems [25]. It has been observed that the particulate matter (PM) level is several times higher than the permissible limits in Punjab during paddy harvesting season.

However, the state government has banned stubble burning. But experts say that implementation is challenging due to the lack of machinery. Between paddy harvesting and growing a new crop, farmers get only 15-20 days, and for that, a large number of straw chopping machines that are expensive will be required for chopping straw instead of burning. That can cause financial implications for rural families which are already in debt. As per National Sample Survey Organization (NSSO) survey, the peasantry of Punjab is the third most heavily burdened state in the country, next to Andhra Pradesh and Tamil Nadu. As per the media report, the rural debt in Punjab is estimated to be more than INR 35000 Crore, resulting in farmers' suicides. As per the latest survey conducted by Punjab Agriculture University, Ludhiana, about 5000 farmers, and farm laborers have committed suicides during the last 10 years. The high debt burden on small and marginal farmers has destroyed many, and they have either sold or mortgaged their land. It has ultimately triggered instances of suicide by many farmers. The solution to imposing this problem could be the utilization of surplus agricultural biomass to generate electrical power. That further can reduce the pollution and effectively improve the present power system along with the betterment of farmer’s economic condition. More research is required to explore the possibilities of effectively using the biomass mentioned above for the power sector.

It is essential to explore the advanced methods for sustainable use of excess biomass from India's urban and agriculture sectors. This biomass merits a great deal of consideration in any energy development program, particularly in Punjab, where natural resources are not available. The consumption of MSW and spare rice straw for power generation can decrease the environmental emissions and act as a source of income for farmers.

1.3 Literature survey

The literature presents a lot of work related to microgrids consisting of various combinations of renewable energy generation technologies. In a case study from the USA, a technical and business framework is presented for a DC microgrid to meet the load demand of a village consisting of 450 houses using solar and biomass (rice husk) based technologies [26]. The proposed hybrid system was feasible with a Levelized cost of electricity (LCOE) of USD 2.05/kWh. Another small-scale power plant is designed that can meet the load and heat demand of rural electrification projects in Italy from solid (rice husk) and gaseous biomass (biogas from olive pomace) [27]. The thermodynamic analysis of three different configurations of the proposed system shows an efficiency of 10% to 17% depending on the adopted technology for the bottoming cycle. Modelling, optimization, including the technical and economic evaluation of a microgrid composed of PV and biomass to electrify a remote apple farm, is presented for Saudi Arabia [28]. This system reports an LCOE of 0.339 USD/kWh. Optimizing a microgrid consisting of PV and gasifier is projected to meet the electricity demand of agriculture wells in standalone areas of Iran. The work reports an effective way to meet the mentioned energy demand regarding economic and reliability [29]. The feasibility of biomass gasification from the palm oil sector for electricity generation in Indonesia is analyzed and reported an LCOE of 0.06 USD/kWh [30]. A microgrid consisting of biomass (agricultural waste), geothermal, PV, and battery backup system is presented to fulfill the energy demand of the vegetable greenhouse system in Romania [31]. This study concludes that the grid extension is not an excellent choice to fulfill the electricity demand of rural areas. Utilizing local renewable energy resources in this village is the most economical feasible and environmentally friendly solution. A hybrid system comprising a gas turbine, biomass gasifier (wood-based), and ground source heat pump based on geothermal energy source is presented for China [32]. This study concludes that partial biomass gasification is a more effective biomass utilization; this approach decreases the reaction time and accelerates the production process.

An integrated system consisting of a gas turbine, gasifier, and solid oxide fuel cell is evaluated and proposed considering three types of biomasses such as MSW, pine sawdust, and fowl manure. The results indicate that fowl manure is best for reducing carbon emissions, and sawdust is best in economic parameters [33]. As per the composition of MSW available for Brazil the technologies landfill gas recovery, recycling and AD along with the sale of digestate and landfill are reported the economically best processing systems [34]. The MSW (high moisture and organic content) of India's capital Delhi has more potential for composting and bio-methanation, whereas commercial, hotel, and institutional waste (less moisture and organic content) is suitable for RDF [35].

Techno-economic and environmental evaluation of a hybrid system composed of the gasifier, gas turbine, and fuel cell is proposed. The study reports that the proposed system has an LCOE 0.086 USD/kWh and a carbon reduction potential of 3564 tonne CO_2/year [36]. The socioeconomic and environmental advantages of using straws for energy production are evaluated and presented for China. The results show that besides reducing the emissions, the utilization of straw for electricity production is profitable and helps create jobs in the nation [37].

Various rice straw processing technologies like combustion, pyrolysis, gasification, and pelletization are analyzed economically. The pyrolysis is reported as the economically best way to process the rice straw in Thailand [38]. A case study from India proposes an optimal stand-alone and grid-connected microgrid comprising wind, PV, biodiesel, diesel, and a battery system. The study evaluated and compared the performance of lead-acid and Li-ion batteries in this hybrid system and reported that Li-ion batteries are techno-economically more viable than lead-acid batteries [39]. A case study from Pakistan evaluates the techno-economic feasibility of a grid-connected hybrid system based on PV, biomass, and wind energy and reports the LCOE as 0.05744 USD/kWh. [40]. Another study from Pakistan proposed and evaluated a PV, biomass, and micro-hydro-based microgrid and reported the system's cost of electricity (COE) as 8.80 PKR/kWh. The study also reveals that the hybrid energy system is the more reliable and prominent solution to the nation's worst energy crises [41]. The technical and financial viability for decentralized electrification based on the gasification of agricultural waste was studied in Ghana which was found uneconomically feasible in five communities without subsidy [42]. The economic feasibility of agricultural biomass utilization for electricity production is analyzed and compared with its incorporation into the soil; results reveal that wheat and rice residue for power production is cost-effective. Further, groundnut shells and cotton stalk residue are not cost-effective for power generation because of their high manure value [43]. A stand-alone microgrid based on PV, biomass, and diesel generators is designed and optimized to meet the load demand of 2000 inhabitants of Bihar (India). Results show that the integration of PV and biomass systems can reduce the LCOE up to 19% and 38% compared to diesel-based power generation [44].

A case study from Peru presents a technical and environmental assessment of energy generation from rice husks. It is reported that the environmental impact of energy generation (1MJ) from rice husk is 80% to 97% less for various environmental categories in compression to energy generation from coal (1MJ) [45]. Another study reports the Life Cycle Assessment (LCA) of biomass gasification integrated combined cooling, heating, and power (CCHP) system [46]. Using biomass for electricity generation is the best way in economic and environmental terms with higher efficiency. LCA methodology is adopted to evaluate and compare the coconut and rice residues for energy generation using gasification, AD, and direction combustion for Southeast Asia. AD is reported as the best means of utilizing this biomass [47]. A microgrid composed of PV, wind, biomass, and Vanadium Redox Flow battery is proposed and implemented virtually in India. From practical experience, this microgrid system is found economically and environmentally viable [48]. The electricity generation from winter cereals biomass by combustion is environmentally more beneficial than electricity generation from natural gas. However, the areas with low productivity land show no significant reduction in emissions compared to natural gas [49].

The environmental impact of various MSW processing technologies is evaluated by many researchers using LCA method [50]. A case study of Macau reported that incineration is the most environment-friendly compared to landfilling, composting, and combination of both the techniques [51]. This technology is most favored for medical waste processing in India [52]. Incineration and landfill gas recovery reduce environmental emissions compared to landfills [53]. However, there is consensus that the processing of MSW by incineration would generally decrease the global warming impact, but with some uncertain effects on human health [54]. Another study highlights the disadvantages of mass burning of MSW for energy generation like gas cleaning and air pollution. It further recommends integrating one or more advanced techniques to give more sustainable results [55]. A case study based in Nigeria confirms that integrated operation of AD and incineration is best compared to landfilling, landfilling with gas recovery and incineration alone [56]. A case study from China reported that refused derived fuel (RDF) production and incineration of MSW are more favorable in environmental terms than its co-incineration with coal [57]. The integrated operation of AD, compost, and landfilling is the preferable combination for Mumbai, India [58]. Another studies reported that AD is best among landfill with gas recovery [59], gasification, incineration and pelletisation [60]. AD is also reported to be environmentally favorable as compared to landfills, incineration, and gasification proposed by [61] and [62]. Another study uses LCA methodology to find the best solution for food waste of Singapore eateries. The AD is reported the most favorable way to process the food waste for electricity generation in comparison to incineration [63]. Considering the heterogeneous nature of MSW, a correlation was developed to predict the higher heating value of MSW accurately [64].

Certain reports on the economic analysis of waste management systems are also available in the literature. A study [65] has considered the environmental and economic evaluation of MSW management scenarios in Wales and found that incineration is environmentally more favorable than landfill and recycling/composting and has a high running cost. Compared to incineration and landfill, the mechanical biological treatment is found to be environmentally favorable but economically weak [66]. The economic and environmental investigation of biogas production for combined heat and power plant, biogas production as fuel for transportation, gasification and incineration are reported for Ireland [67]. The results indicate that biogas production for both the applications is cheap and less polluting than thermal technologies. AD, gasification, composting and recycling are evaluated economically in a case study from Abu Dhabi. The combination of recycling and bio-ethanol production using gasification is found economically more beneficial than any other method [68]. A Case study from Brazil [69] analyses the economic and environmental factors of incineration and landfill with gas recovery and found that incineration is favorable in both factors. Solid recovery fuel reported the highest energy recovery potential as compared to biogas production and landfill gas recovery [70]. It has been observed that a novel design that combines plasma gasification (treating medical waste) and incineration (processing MSW) can reach the waste to electricity energy efficiency of 34.91% [71].

A study [72] has proposed the present MSW management system (Mumbai, India) in economic terms that consist of open dumping, incineration (medical waste only), and composting and found this system inefficient. Another study proposed in [73] found that the bioreactor landfill system is more favorable in environmental and economic terms than open dumps and landfills (with and without gas recovery). A study from Turkey evaluates eight economic and environmental scenarios and found that recycling and land filling are prominent means for MSW management [74]. Compared to gasification, landfill and incineration; AD is reported to be favorable in economic and environmental terms for China [75]. The potential of carbon reduction and energy generation from MSW is evaluated by considering different scenarios for Malaysia. Incineration is reported as the best way to produce electricity from MSW in both economic and environmental terms [76]. A case study from the USA analyzed and compared various alternate technologies (AD, gasification, incineration, and fermentation) using industrial ecology approach for MSW processing. Results predict that AD, gasification, and fermentation are economically and environmentally feasible solutions for MSW processing [77].

Many studies in the literature evaluate the environmental sustainability of rice straw to energy generation technologies using the LCA tool. LCA of rice straw consumption systems includes incineration, fermentation, dimethyl ether, and incorporation into the soil presented in [78]. Results found that bio-ethanol production has the highest environmental sustainability. Bioethanol production in India is a clean, renewable, and sustainable fuel [79], but its commercial-scale production is a significant challenge [80]. Another study from India reported that compared to gasoline, the ethanol produced from rice straw could reduce the (greenhouse gases) GHG emissions by up to 89% from rice straw [81]. A case study from Thailand shows that ethanol production is favorable to power generation [82]. A case study from India shows that electricity and biogas production is environmentally more favorable than using straw as animal fodder and its incorporation into fields [83]. A Malaysia case study finds that electricity generation from rice straw can reduce emissions of about 1.79 kg CO_2-eq/kWh and 1.05 kg CO2-eq/kWh compared to coal and natural gas [84]. The rice straw-based heat energy generation is reported to be better than soil incorporation, and open-field burning with a net GHG avoided emission of -61 kg CO_2-eq Mg^{-1} [85]. A study [86] reported that bioethanol production from Napier grass is more environmentally favorable than rice straw. However, the mass production of biofuels is difficult due to several technological and environment issues [87]. For the developing countries technologies AD (organic waste), incineration (mixed waste), pyrolysis and gasification (woody biomass), and landfilling (inert waste) are reported most feasible [87].

Specific reports on an economic analysis of rice straw processing systems are also available in the literature. The economic feasibility of biomass-based combustion projects in Thailand of capacities 5, 8, 10, 15, and 20 MW are analyzed. The results indicate that COE varies from 0.0676 USD/kWh at 20 MW to 0.0899 USD/kWh at 5 MW [88]. The financial feasibility assessment of rice straw incineration-based power projects of different scales in Thailand is performed and found that these facilities are financially feasible and profitable [89]. The sale of rice straw to the local energy feedstock market is reported to be a better solution than its incorporation into the field [90]. One of the studies employs micro aerobic pre-treatment using different microbial reagents combined with oxygen to increase the energy conversion potential of rice straw via AD in an efficient manner. They concluded that micro aerobic pre-treatment is an appropriate technique for the energy conversion efficiency of rice straw [91]. A case of Vietnam shows that the country has the potential to generate 2,565 MW of electricity from rice straw [92]. A study from Egypt reveals that the utilization of rice straw as an energy source will reduce the consumption of fossil fuels and mitigate the problem of air pollution. The estimated potential of Egypt from rice straw is 4193 GWh and 25647×10^{6} MJ of biogas energy [93].

1.4 Gaps in study

Recently, the hybrid systems of solar, wind, biomass, and electricity storage systems have been explored for various countries' feasibility analyses. Among all the proposed systems, the use of biomass is inadequate and kept on the least priority (if considered) because biomass has fuel cost. In contrast, wind and solar energy are available free of cost. The various hybrid energy generation systems that consist of biomass energy sources are analyzed to estimate the environmental impact on various countries. These hybrid systems based on local renewable energy resources are found to be environmentally more sustainable as compared to conventional electricity generation systems. The biomass utilization in hybrid systems is limited and restricted to agricultural, animal manure, and woody biomass only, and MSW is not used to design a hybrid system. In various case studies, MSW processing technologies are evaluated individually and compared. From the outcomes of these studies, it can be concluded that electricity generation is a more sustainable approach than conventional MSW handling systems. Further, compared to old technologies, advanced technologies, such as AD and gasification, show far better environmental results. The design and evaluation of an MSW-based microgrid that integrates advanced MSW processing technologies with renewable technologies are not yet explored.

Further, most agricultural biomass resources considered are limited to rice husk, palm oil, and olive pomace. In countries like India, where rice straw utilization has become a severe matter at the current time due to open burning issues, there is a desperate requirement to propose and evaluate the most progressive technologies and hybrid systems to establish the most suitable way. The processing of surplus rice straw in microgrids for electricity generation can open new doors for sustainable utilization. However, studies related to the conceptualization of rice straw-based microgrid that processes the straw on priority and other renewable energy sources are not reported yet.

As per various case studies reported in different countries, an important point related to biomass-based systems is noted. The performance of waste processing technologies is sensitive to the technological and socio-economic environment of the country. The processing of any waste has several techno-economic and environmental obstacles unique to each country and type of waste. Sustainable utilization of any waste is a broad perception that should be analyzed individually at the ground level of a particular nation [94]. Factors like the cost of technology and the economic value of the produced product are enormously dependent on each country's local market and policies [95].

Further, for any nation, the policies related to various technologies might take concern. The success of renewable energy sources in the power system depends on three major factors: economic cost, environmental impact, and reliability [6]. The planned system must be economically feasible and environmentally sustainable and simultaneously must be reliable to meet the desired load demand [96]. Therefore, as per the type of biomass, the characteristics assessment and comparative evaluation of various technologies in economic and environmental parameters are necessary to select a particular technology. The study related to characteristics assessment of biomass for MSW and rice straw processing technologies in economic and environmental terms for India is not explored yet. As per the literature survey, the objectives and contributions of the proposed research are presented in the next section.

1.5 Objectives and contribution of the proposed research

The motivation of this work is to propose MSW and rice straw-based microgrids for India by selecting the most sustainable waste processing technologies. This research proposes the characteristics assessment of various MSW and rice straw processing technologies in economic and environmental terms for the Indian scenario. After that, by comparative evaluation, the most sustainable technologies in economic and environmental terms are selected, modeled, simulated, and integrated to design microgrids. Therefore, this research work presents a justifiable contribution to the literature by evaluating various MSW and rice straw processing technologies in the Indian scenario. The most sustainable technologies have been identified, developed modeled and simulated for the proposed MSW and rice straw-based microgrids. The study also highlights the economic and environmental benefits of proposed microgrids. Based on the outcome of the literature survey, the objectives of the present research proposal are given below.

1. Characteristic assessment study of selected power plants.
2. Development of power system models and their simulations.
3. Integration and conceptualization of microgrid system.

1.6 Overview of thesis chapters

The thesis has been organized into four chapters. Chapter 2 of the thesis presents the characteristic assessment and comparative analysis of various MSW and rice straw processing technologies in the Indian scenario. Chapter 3 presents the conceptualization, modelling, integration, techno-economic, and environmental evaluation of MSW and rice straw-based microgrids. Finally, in chapter 4 conclusions are presented that summarize the study results.

CHAPTER 2

Characteristic assessment and comparative evaluation of municipal solid waste and rice straw processing techniques

2.1 Introduction

Any waste-to-energy generation system has some economic and environmental barriers typical to the type of waste that further varies from country to country. Therefore, for a particular country, it is necessary to evaluate the biomass-based energy generation system at the ground level. Further, to find a sustainable waste management system, it is necessary to simultaneously evaluate the techniques, both in economic and environmental aspects [92], for a particular location considering common waste handling system factors. Because of economy and environment are the most vital factors of sustainability for the waste management system. Economic and environmental factors can help Government organizations and strategy-making committees make proper decisions for maintaining a sustainable waste management system. In this chapter, two types of Indian waste MSW and rice straw are selected to accomplish this plan. Various technologies to process MSW and rice straw are evaluated separately using industrial ecology methodology and the LCA tool.

In case of MSW, the landfilling is taken as the common way to handle MSW, whereas, the technologies including AD, compost, RDF, incineration and gasification are selected as the alternate systems to process MSW. Along with the electricity generation technologies (AD, gasification and incineration), other technologies such as RDF and composting are selected to compare and find the most sustainable means to process the MSW. The techno-economic and environmental parameters of all the selected technologies are assessed in the Indian scenario considering the virtual operation of the existing plants. As per the selected methodology, a set of equations is developed to evaluate MSW processing technologies (section 2.3), and detailed calculations are provided in the supplementary information (**Appendix A**). The selected technologies are evaluated in detail at each step of the process and compared in economic and environmental terms considering a population size of one million (section 2.3).

In the case of rice straw, the chemical properties of straw may not differ for various countries. But, factors like the cost of technology and the economic value of the produced product are enormously dependent on each country's local market and policies. Further, for any nation, the policies related to various technologies might take concern. Even for a particular technology like AD processing MSW and rice straw, the policies are different for different feedstock since the issues like collection, handling, storage, amount, and value of the product produced are different for MSW and rice straw. Also, the processing emissions for both systems are different. So, it is necessary to evaluate rice straw processing technologies individually for a particular country. In section 2.4, the characteristic assessment and comparative analysis of various rice straw processing technologies are proposed for India. The techniques such as incineration, gasification, AD, fermentation and integrated operation of fermentation and AD are selected to evaluate rice straw processing system. Considering the virtual performance of the existing plants for electricity and ethanol production in India, each technique's simultaneous economic and environmental evaluation is presented. As per the selected methodology, a set of equations is developed for evaluations of rice straw processing technologies (section 2.4), and detailed calculations are provided in the supplementary information (**Appendix B**). All the selected technologies are evaluated in detail at each step of the whole process and compared in economic and environmental terms.

2.2 Methodology

The term waste is not in favor as it implies something to be eliminated. Another opinion occurs by saying the word sustainable resource management to gather the thought of productivity and sustainability. “Waste” does not mean the potential utilization of materials in various applications. To identify and realize the use of otherwise discarded materials Industrial ecology-based symbiotic system approach is required. The term industrial ecology was first introduced by Frosch and Gallopoulos in 1989 [97]. It represents an industrial ecosystem where waste from one process can serve as a raw material for the other process to optimize the whole system. Aspects of the industrial ecology and its description are reported in [98]. Further, one of the research provides an industrial ecology-based methodology for MSW [97]. This methodology focuses on energy conversion's economic and environmental facts and various products. However, the environmental results provided by this methodology are limited to the type and amount of pollutants. This methodology does not estimate the impact of these pollutants on the environment. So present study uses LCA methodology and industrial ecology methodology to evaluate the MSW and rice straw processing systems. LCA is an appraisal methodology to assess and quantify the environmental impacts of the process, product, and service through all phases of their life cycle [99]. LCA is commonly used to analyze the environmental assessment of bioenergy systems. International Organization for Standardization (ISO) 14040:2006 is used for LCA methodology. This method measures the potential environmental damage of air, liquid and solid emissions using appropriate equivalence factors to selected reference compounds for several impact categories.

Table 2.1: Characterization factors of Environmental Impact

Environmental Impact Category	Characteristic Substance	Characterization factors					
GWP	CO_2	CO_2	CH_4	CO			
		1	25	2			
AP	SO_2						
		SO_2	HCL	H_2S	NO_X	HF	
		1	0.88	1.88	0.7	0.6	
POCP	C_2H_4	C_2H_4	CH_4	CO	NO_X	VOC	
		1	0.006	0.027	0.03	0.6	
EP	PO_4	PO_4	NO_X	BOD	COD	Total N	P
		1	0.13	0.05	0.022	3.07	3.06

Four impact categories, including global warming potential (GWP), acidification potential (AP), photochemical oxidants creation potential (POCP) and eutrophication potential (EP) are selected for this study. The emission of greenhouse gases increases the atmospheric temperature resulting global warming. The GWP is expressed as CO_2 equivalent for all greenhouse gases emission using an equivalency factor over 100 years (GWP100). Acidification is when the gas emissions related to this category will convert to acidic substances and result in acid rain. AP impact is calculated as SO_2 equivalent for all acidifying emissions. The pollutants belonging to POCP category reacts in sunlight and results as formation of smog. The POCP is expressed as C_2H_4 equivalent of all the emissions contributing to this category. The enrichment of water sources due to chemical nutrients is called eutrophication. It enhances the production of algae and aquatic plants. EP is calculated as PO_4 equivalent of all emissions contributing to this category. The pollutants such as CO_2, CH_4 and CO are taken under GWP category; SO_2, HCL, H_2S, NO_X

and HF for AP; CH_4, CO, NO_X and VOC under POCP; NO_X, Total N, BOD, COD, and phosphorous for EP. Characterization factors of environmental impact for all the selected pollutants are shown in Table 2.1.

2.3 Evaluation of MSW processing technologies

The systematic procedure for selecting common and alternative techniques is represented in Figure 2.1. Landfilling is considered as a common technique for total MSW generated per day. Among the alternative techniques, AD and compost are considered to process the wet portion of MSW whereas; RDF, gasification and incineration are selected to process the dry portion. For each alternate technology, the output product is shown along with a suitable type of feedstock. The amount of MSW that is not processed and the waste product of alternative techniques is considered residue that needs to be landfilled.

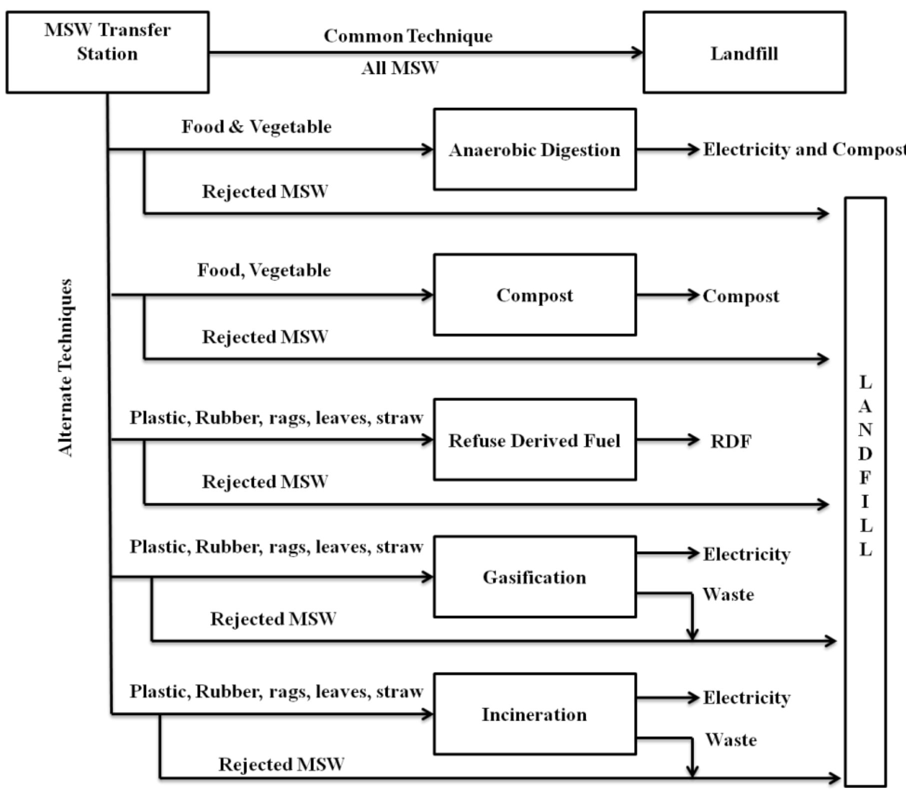

Figure 2.1: Common and alternative technologies for the processing of MSW

Figure 2.2 shows various steps of industrial ecology methodology for economic and environmental evaluation of selected techniques. Two different streams, wet and dry, are made to compare the performance of alternative techniques. In the first step for a particular location, one must find the amount of suitable feedstock per day available for each technology. As per the efficiency of technique and feedstock availability, the product per day for all alternative techniques can be calculated. Then the distance of each plant and landfill site from the city is calculated. As per the total amount of waste available, the landfill cost and transport cost to the landfill for a unit tonne of waste is calculated. The Processing of MSW by any alternative technology will eliminate the landfill cost and landfill transportation cost.

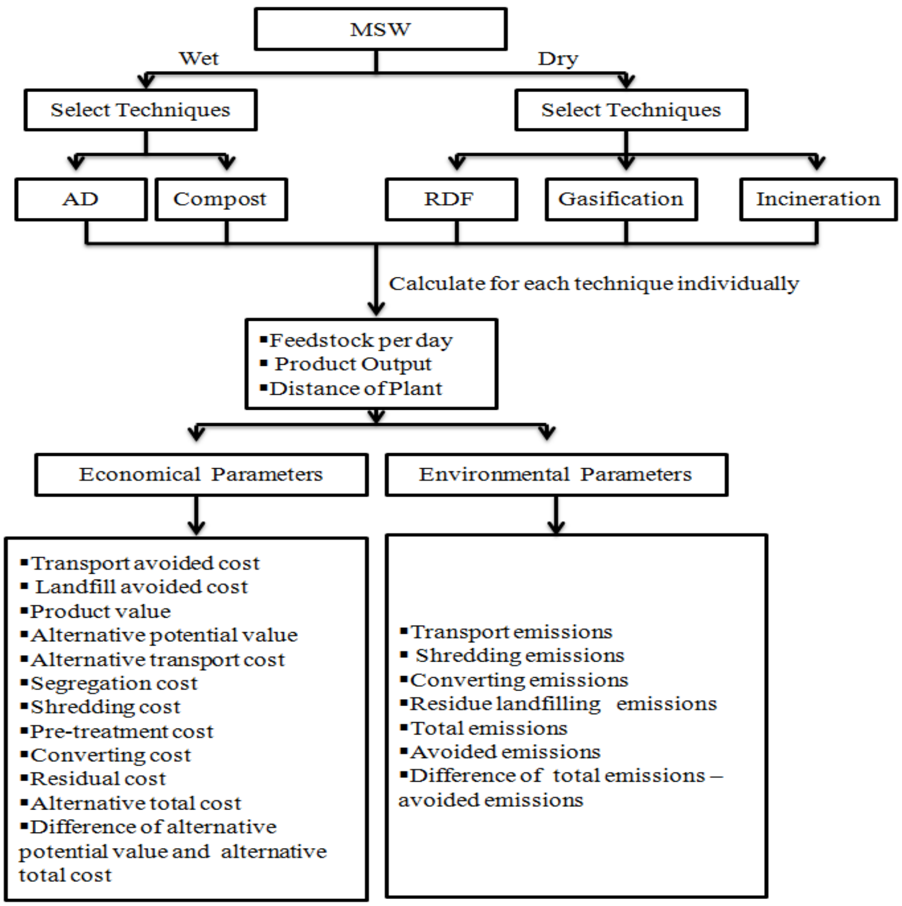

Figure 2.2: Schematic representation of proposed methodology

As per the amount of waste per day processed by a particular technique, the landfill cost, including transport cost, can be calculated for that amount of waste. These costs are considered transportation avoided costs and landfill avoided costs per day for a particular technology. The total avoided cost (C_{av}) is be calculated as

$$C_{av} = C_{avt} + C_{avl} \tag{2.1}$$

Where C_{avt} is transport avoided cost and C_{avl} is landfill avoided cost.

Then product value of each alternative technique can be calculated as per the efficiency of a particular technology, the quantity of a product, and its per-unit price. The summation of product value and avoided costs gives each plant the alternative potential value (A_{pv}). That is computed as mentioned below.

$$A_{pv} = P_v + C_{av} \tag{2.2}$$

Where P_v is product value in economic terms.

To estimate the cost of feedstock (C_f) by different techniques equation (2.3) is used.

$$C_f = C_t + C_{sg} + C_{pt} + C_{sh} \tag{2.3}$$

Initially, the alternative transportation cost (C_t) is estimated, which depends on the amount of waste and the distance of each plant where waste is transported. As per the amount of feedstock available for each plant, segregation cost (C_{sg}), pre-treatment cost (C_{pt}), and shredding cost (C_{sh}) per day are calculated.

The converting cost (C_c) for each alternative is calculated as per capital cost (C_{cap}), operating cost (C_{op}), and maintenance cost (C_{ma}) for processing per tonne of MSW and the total amount of MSW processed per day as shown in equation (2.4).

$$C_c = C_{Cap} + C_{op} + C_{ma} \tag{2.4}$$

For each alternative technique, the residue transportation (C_{rt}) and its land fill costs (C_{rl}) per day can be calculated as per the distance of the landfill and the amount of residue. Then the total residue cost (C_r) is calculated as

$$C_r = C_{rt} + C_{rl} \tag{2.5}$$

Alternative total cost (C_{at}) per day for each plant is summarized as per feedstock cost (C_f), converting cost (C_c), and residue cost (C_r) as shown in equation (2.6)

$$C_{at} = C_f + C_c + C_r \tag{2.6}$$

Finally, the difference between each plant's total alternative potential value (equation 2.2) and total alternative cost (equation 2.6) can be calculated.

To analyze environmental parameters, one must calculate the transportation, shredding, converting, and residual landfilling emissions per day for each alternate technology. The transportation emissions are the emissions by utilization of diesel in the transportation of MSW to a particular plant. Shredding emissions are the emissions with electricity consumed by the shredder. Converting emissions will differ largely for various technologies as it depends upon the way of processing MSW in respective technologies. Residue landfill emissions are the emissions by transporting and land filling that amount of MSW not processed by alternate technology plus the waste product from the alternate technology. Processing MSW by any technology saves the land fill emissions by replacing these emissions with the alternative technology emissions. The land fill and transportation emissions per day can be calculated as per the total amount of MSW generated per day. The difference between each technology's avoided and alternative technology emissions can be estimated individually.

The difference between alternative potential value and alternative costs for technologies considered can be computed for each stream. The technique with a greater difference is economically more profitable. The negative difference indicates that the cost of technology is higher than the alternative potential value. Also, the technique with higher reduced or least emission increased is more eco-friendly. The integrated operation of best-performing techniques from both the streams may generate the most optimum results.

2.3.1 Selected technologies and their characteristics assessment

This section introduces selected technologies and characteristics assessment of economic and environmental parameters in the Indian scenario. The assessment of MSW processing starts from its transportation. The emission from the transportation of MSW is calculated as per the emission factors for trucks given for Indian transport [100], as shown in Table 2.2. The emissions from the shredding of MSW are calculated per the electricity consumed in shredding taking emission factors for the Indian grid mix [101], as shown in Table 2.2. It has been assumed that electricity and compost will replace coal-based electricity and chemical fertilizers. The coal-based electricity emissions for Indian grids are referred from [102]. The emissions from the production of chemical fertilizers are referred from [103]. The detailed calculation is provided in the supplementary information (**Appendix A**).

Table 2.2: Transport and grid emissions

Emissions	CO_2	CH_4	CO	NO_X	SO_2	PM	VOC
Transport emissions kg/km	0.512	0.9E-04	0.36E-2	0.63E-2	0.142E-2	0.28E-3	NA
Grid (mix) emissions kg/kWh	1.11	0.445E-2	0.117 E-2	0.223E-2	0.277E-2	0.314E-2	1.01E-07

2.3.2 Common technology: Landfill

The Landfill is one of the most common techniques to dispose of organic waste; the (US EPA) presents several components of landfill leachate and air emissions. Landfill Gas (LFG) mainly consists of methane and carbon dioxide [105]. It occurs due to the decomposition of biodegradable MSW. The LFG emission rate is initially higher than the landfill site, but it decreases gradually after several years. The utilization of LFG after this stage becomes economically unfeasible.

The quantity of LFG emitted by a landfill depends upon the depth of the disposal site and climate including average temperature and precipitation, composition of MSW and dumping in past. The wet climate, higher content of food and presence of worms makes the decomposition rate of MSW faster in India than developed countries [106]. The capital cost of a landfill in India is INR 13 crore (USD 2 million) for 500 tonne per day (tpd) for 6 years [107]. Operating and maintenance cost is 0.7% per year of the capital cost [60].

The methane and carbon emissions from landfills are estimated using Landgem model version 3.02 for the MSW considered for this study. As per the composition of waste and Indian environment, the value of methane generation potential L_o is taken 70.2 m^3/tonne, and “k” that is methane generation rate is taken as 0.032/year [108]. The emission factors for a unit tonne of MSW are calculated from the total landfill emissions (including emissions up to 100 years after landfill closure) and total MSW disposed to landfill (240 tpd of MSW for 20 years) and shown in Table 2.3. Emission of gases SO_2, HCL, NO_X, HF, VOC, H_2S, CO and emissions to water are taken from [92] and [109] with consideration that 80% of the leachate [110] is treated and 20% leaks to aquatic recipients as shown in Table 2.4

Table 2.3: Emissions to air (kg/tonne)

Gases	Landfill	AD		Compost	RDF	Gasification	Incineration
		Biogas production	Biogas engine				
CO_2	126.66	15	NA	206.28	59.51	922.34	922.34
CH_4	46.25	0.4E-2	1778E-2	2.388	17.79E-2	NA	8.8E-2
SO_2	5.3E-2	1.7E-3	NA	77.65E-3	10.47E-2	5.2E-2	3.27E-1
HCL	3E-3	NA	NA	1.29E-2	NA	3.2E-2	0.79E-1
NO_X	0.68	4.6E-2	79.9E-3	4.29E-2	28.94E-2	0.78	1.24
HF	3E-3	NA	NA	NA	NA	3.4E-4	0.1E-2
VOC	6.4E-2	NA	3.96E-3	3.18E-5	0.0516	1.1E-4	0.8E-2
CO	7.8E-3	1.1E-2	12.7E-2	1.49E-4	0.0507	0.10	0.383
H_2S	0.11	14.19E-4	NA	0.404E-3	NA	NA	NA

Table 2.4: Emissions to water (kg/tonne)

	Landfill	AD	Compost
COD	0.171E-2	0.27E-5	0.14E-3
BOD	0.974E-3	0.69E-6	--
Total N	0.94E-2	0.27E-6	0.155E-2
Phosphorus	0.76E-4	--	--

2.3.3 Alternate technologies

Several technologies exist in the case of MSW processing. The selected technologies are described below.

2.3.3.1 Anaerobic digestion

The AD of biomass basically follows hydrolysis, acidogenesis, acetogenesis, and methanogenesis processes [5] [111]. In methanogenesis stage the products from the previous phases are converted into CH_4 and CO_2 by methanogenic micro-organisms [112]. The end product is a combustible gas called biogas [113], which has energy about 20–40% of the lower heating value of the feedstock. It is a mixture of mainly CH_4 (60-70%) and CO_2 (30-40%) with small quantities of other gases such as hydrogen sulphide, nitrogen, hydrogen and carbon monoxide [114]. Biogas can be used as energy source for transport and energy sector [7] also with the help of spark ignition gas engine it can be utilized to produce electricity [115]. AD can reduce the volume of waste up to 70% and the remaining digestate can be used as fertilizer [116]. This technology in India with initial research efforts in 1920 gained momentum around 1995-1992 due to subsidies interdicted by Government. With the efforts of the MNRE seven biogas plant designs were approved in 1996 and up to 2006, 3.89 million numbers of such small family type plants were successfully installed in the country [117]. At the end of 2015, 48.34×10^3 biogas plants were installed from the estimated potential of 123.39 million [118]. As per the latest information available with MNRE, India has a total installed capacity of grid-connected waste to power 115.08 MW and off-grid waste to energy 161.39 MW [119]. But in the case of solid organic waste, India has limited experience with AD technique except for animal manure and sewage sludge [120].

Department of economic affairs (New Delhi) reported the capital cost for AD plant INR 40.21crore (USD 6.18 million) with a capacity 300 tpd for MSW processing. Operating and maintenance costs are INR 2.72 crore/year (USD 0.41 million/year) with a 4.83% annual increase for 20 years of plant life [121]. $1m^3$ of biogas with 60% methane can produce 2 kWh of usable electricity [122]. In the present case, the biogas yield of MSW is 55 m^3/tonne [123] which can generate 110 kWh of electricity. Ministry of New and Renewable Energy Resources (MNRE), Government of India, provided tariff rates of electricity for AD is INR 7.60 (USD 0.116) per kWh [124]. The compost production potential of AD is 8.2% of the total feedstock processed with a selling price of INR 1200 (USD 18.46)/tonne [125].

The environmental impact of AD is calculated as per the emissions from biogas production and its utilization in biogas fueled engines. For biogas production, the emission factors for CO_2, CH_4 CO, NO_X and SO_2 are taken from [126] as shown in Table 2.3. H_2S emissions are calculated considering 1% leakage of biogas during production [127]. The emissions from biogas fueled engines are calculated from [128] and emissions to water are adopted from [61] and shown in Table 2.4.

2.3.3.2 Compost

There are two ways of composting i.e., aerobic composting and vermi composting. Generally, composting means the bacterial conversion of the organics present in MSW in the presence of air along with hot and moist conditions [129]. The end product found after a bacterial activity is compost, i.e. humus, which is very rich in agricultural value. Composting can reduce the volume of MSW 40-50% [130]. Composting can be done using various means, either manual plants in smaller urban areas or mechanical composting plants running in big cities. In the case of vermi composting, the organic waste can be stabilized by the combined action of earthworms and aerobic microorganisms. Primarily, through extracellular enzymatic activity, the biodegradable decomposition of the organic waste occurs, and then partially decomposed the earthworms eat organic waste. This is further decomposed in the gut of the worms. The final product from a worm can be used as a bio-fertilizer [131].

Karnataka Urban Infrastructure Development and Finance Corporation reported the capital cost of composting INR 28.34 crore (USD 4.36 million) for 200 tpd. Operating and maintenance cost is INR 2.32 crore (USD 0.356 million) per annum for a capacity of 200 tpd [132]. For this study compost production potential is considered 32.8% [133] of the total MSW processed. The selling price is INR 2500 (USD 38.46)/tonne [124].

The emissions CO_2, CH_4 and Total N from composting are calculated according to the balance of carbon and nitrogen as shown in Table 2.3. It has been assumed that 70% of total carbon is released into the air. The CO_2 and CH_4 emissions were calculated as 95% and 1.1% of the carbon released into air. Also, 68% of nitrogen is released into the air in the form of N_2, N_2O and NH_3. The total N is assumed to be released 3% [58]. Other emissions like CO, H_2S, SO_2 , NO_X , HCL, and VOC are adopted from [134]. The emissions to water from composting of MSW are taken from [51] and shown in Table 2.4.

2.3.3.3 Refuse derived fuel

Refuse-derived fuel is an enhanced solid fuel from MSW. Making RDF from MSW can reduce the pressure on landfills to a significant level. Fluff/pellets can be utilized by a gasification or incineration plant to produce electricity. Also, RDF can be burned along with conventional fuels to produce heat energy. RDF consists of more combustible material concentration than the parent MSW. The thorough pre-separation of recyclables along with their complete shredding, drying, and densification is done under the whole process of RDF that makes the end product easy to handle [135].

From waste, the glass and plastic material is separated manually or by using separation devices and this is followed by shredding which reduces the feedstock remaining up to eight inches. The mixture left behind consists of food wastes, non-separated paper, some plastics, and green wastes. Drying to less than 12% moisture is typically accomplished through forced-draft air. The next step is the densification processing of the material to produce pellets [136]. The quantity and composition of RDF depend upon the nature and extent of waste, way of collection and pre-processing [137].

In the Indian scenario, 750 tonne of RDF can be produced from 1300 tonne of MSW [138]. Typically RDF obtained from Indian MSW has a calorific value of 3100 kcal/kg and moisture content less than 15% [139]. Investment costs lie in INR 140 – 370 (USD 2.15 to 5.69) per tonne for annual capacities of 45,000 to >500,000 tonne of input MSW. Operation and maintenance costs are INR 120 – 290 (USD 1.84 to 4.46) per tonne [140]. The process includes mechanical separation, shredding, blending, drying, pelletization and packing. [124] fixed the price of RDF as INR 1500 (USD 23)/tonne.

The emissions related to RDF making are estimated as per the utilization of electricity and diesel as shown in Table 2.3. Electricity and diesel consumption for making one tonne of RDF from MSW consume 64.3 kWh of electricity and 10 liters of diesel (including loading and transportation of RDF) [141]. All the pollutants related to electricity are taken from [101] for the Indian grid (mix**).** The emission factors for the consumption of diesel are taken from [100]. Emissions from RDF utilization are calculated following the burning of RDF and the amount of coal replaced in cement kilns. Considering the calorific value of RDF 12.9 GJ/tonne and coal 23 GJ/tonne [142], one tonne of RDF can replace 560 kg of coal. The emissions related to the combustion of coal and RDF in cement kilns are adopted from [142]. The net emissions from RDF utilization are calculated as the difference of emissions from 560 kg of coal and one tonne of RDF.

2.3.3.4 Gasification

Gasification is the technique for converting the organic fraction of biomass into a combustible gas mixture known as syngas (mixture of hydrogen, carbon monoxide, and carbon dioxide). This can be done by the partial oxidation of biomass at high temperatures i.e. in the range 800ºC–

900ºC. This gas can be further burnt directly or used as a fuel for gas engines and gas turbines to produce electricity [143]. Gasification can process a wide range of biomass, including wood, corncobs, corn stalks, coconut shells, fronds, sawdust, MSW, and different husk types, like rice, coffee, and groundnut [144]. This system's critical components are a gasifier that produces syngas, a clean-up system that removes the dangerous components of syngas, energy recovery system. With producer gas having a heating value of 15 to 20 MJ/N m^3, a net electrical efficiency of 23-25% can be achieved [60]. Due to highly focused policies by the Indian Government, biomass gasification has gained momentum [144]. MNRE plays a vital role in promoting biomass gasifier power plants to generate electricity by utilizing available biomass resources. The plants are installed in rural areas where biomass is available abundantly [145]. The total installed capacity of biomass gasifiers in India was 243 MW in 2009 [60].

Gasification reduces 50-90% volume of waste processed [116]. The syngas composition for Indian MSW is not yet reported. However, the power potential of Indian MSW is reported 685 kWh/tonne MSW for conventional gasification [146]. But from practical experience, Municipal Corporation of Pune reported power generation of 2.5 MW from 250 tonne of MSW per day [147]. This is the only plant in India processing MSW using gasification technology. The corporation plans to extend the plant up to 700 tpd for 10 MW of electrical power output. The capital cost of a gasification plant for processing MSW in India is INR 15.57 crore (USD 2.35 million)/MW [148]. The annual operating and maintenance costs are 5.82% of the capital cost with an escalation rate of 5.72%. Tariff rate of electricity for gasification is INR 6.50 (USD 0.10)/kWh [124]. In case of gasification CO_2 emissions are calculated by tier 1 methodology in accordance to the composition of waste processed. This approach uses the gain-loss method presented in the Intergovernmental Penal of Climate Change (IPCC) guidelines workbook and the default emission factors given in IPCC guidelines workbook and reference manual. All other emissions for gasification are taken from [149] and shown in Table 2.3.

2.3.3.5 Incineration

In this technique, controlled and complete combustion of biomass occurs in the presence of oxygen at high temperatures, leading to the destruction of biomass and energy recovery. This works in the temperature range of 980 ºC and 2000ºC [150]. The most crucial feature of the incineration technique is that it can reduce the volume of combustible solid waste by up to 90%

of its original content [127]. For incineration, MSW consisting of highly combustible material with low moisture and inert is suitable. Practically 65 to 80 % of waste can be recovered as heat energy, used to produce electricity, or for thermal applications [136]. The significant components of an incineration plant include waste handling, steam generation system, flue gas cleaning system, power generation apparatus, cooling system, and residue handling system [136]. Incineration is not much practiced in Indian cities, because of the high organic material and moisture content amounting to 40–60% and low calorific value 800–1100 kcal/kg in MSW. However, in case of medical waste disposal incineration is common mean in India [52]. Power potential of incineration in India is reported at 167 kWh/tonne with a net electrical efficiency of 15% [60]. The capital cost of an incineration plant in India reported by the department of economic affair (New Delhi) is INR 60 crore (USD 9.23 million) for a capacity of 700 tpd. Operating and maintenance expenses are INR 3 crore (USD 4.61 million)/year with 15 years of plant life [121]. The electricity tariff rate for incineration is INR 6.50 (USD 0.10)/kWh [124]. CO_2 emissions from incineration are calculated according to the composition of waste using tier 1 methodology. Pollutants SO_2, HCL, NO, and CO are taken from (US EPA) and HF, CH_4, and VOC [149] and are shown in Table 2.3.

2.3.4 Case Study for evaluation of MSW processing technologies

For the analysis of considered techniques, the state of Punjab has a waste generation rate of 0.37 kg/day/ person. The population size is taken one million, which can generate 370 tpd of MSW with the composition reported in [123]. Taking collection efficiency 65% as provided by Central Pollution Control Board (CPCB) [151] 240 tpd of MSW is available for processing. The suitable amount of MSW attainable after segregation is estimated after manual segregation of mixed MSW. After segregation, the fraction that can be achieved is 35% food and vegetable waste, 12.4% leaves and straw, 12.3% rags, 0.5% rubber, 6.5% plastic, and 3.2% paper. Out of 240 tpd of collected MSW, 167 tpd is available to process after segregation. Food and vegetable waste is suitable for AD and compost. Where plastic, rubber, rags, leaves, and straw is suitable for RDF, incineration, and gasification. From total MSW as per the waste composition, 84 tpd is suitable for AD and composting. While selecting RDF, incineration and gasification processing techniques 76.08 tpd of MSW is appropriate. Waste paper has not been selected for any processing technique due to deforestation effect. Government of Punjab focuses on recycling of paper and reported the most efficient way is selling of paper by the waste generators to the recycling plant directly [152].

The distance of the landfill is taken 20 km from the city; for processing plants, it is assumed as shown in Table 2.5. Pre-treatment costs for all the plants are not applicable here because no extra pre-treatment is required for MSW processing by the selected technologies. Source segregation of MSW requires some infrastructure which further requires some investment. This cost can be saved if the people are aware and motivated to segregate the waste at their end. According to Municipal Solid Wastes (Management and Handling) Rules, 2000, the municipal authority shall undertake a phased program to ensure community participation in waste segregation. In this study, segregation of waste at the collection end is assumed. Both the economic and environmental results are calculated and presented on daily basis. The detailed calculation of economic and environmental analysis for given technologies is provided in the supplementary information (**Appendix A**).

Table 2.5: Alternative technologies with their respective products and system parameters

System parameters	AD	Compost	RDF	Gasification	Incineration
MSW processed (tpd)	84.00	84.00	76.08	76.08	76.08
Product/day	9.25 MWh*	28.00 tonne	43.89 tonne	18.25 MWh	12.70 MWh
One way distance to plant (km)	10	20	20	40	40

***** Along with 9.25 MWh of electricity AD also produces 6.9 tonne of compost/day

2.3.5 Economic analysis

Table 2.5 shows the product of each plant that depends upon the amount of MSW processed yield of MSW and the efficiency of a particular technology. After analyzing all the factors as per the Indian experience discussed above, the per day output product is for AD plant 9.24 MWh/day, gasification 18.25 MWh/day and incineration 12.7 MWh/day. Also, 28 tpd of compost and 43.89 tpd of RDF can be produced through composting and RDF plants, respectively. Along with the electricity, AD is also producing 6.9 tpd of compost. The detailed calculations are provided in the supplementary material.

Table 2.6: Economic analysis of the alternative technologies on a daily basis for the processing of MSW generated by the population of one million (represented as INR/day)

Economic parameters (INR/day)	AD	Compost	RDF	Gasification	Incineration
Transport avoided cost	6.98E+3	6.98E+3	6.32E+3	6.32E+3	6.32E+3
Landfill avoided cost	1.04E+4	1.04E+4	9.42E+3	9.42E+3	9.42E+3
Product value	7.86E+4	7.00E+4	6.59E+4	1.19E+5	8.26E+4
Alternative potential value	9.59E+4	8.74E+4	8.16E+4	1.35E+5	9.83E+4
Alternative transport cost	4.66E+3	6.98E+3	6.32E+3	1.06E+4	1.06E+4
Shredding cost	3.57E+3	3.57E+3	3.23E+3	3.23E+3	3.23E+3
Converting cost	3.64E+4	4.30E+4	3.50E+4	3.52E+4	2.09E+4
Residual cost	3.23E+4	3.23E+4	3.39E+4	3.86E+4	3.55E+4
Alternative total cost	7.68E+4	8.58E+4	7.85E+4	8.75E+4	7.01E+4
Difference = alternative potential Value – Alternative total cost	1.91E+4	1.58E+3	3.14E+3	4.70E+4	2.83E+4

Processing MSW by any alternative technology will eliminate the landfill cost and the landfill transportation cost. These costs are calculated for each plant and indicated in Table 2.6. As per the capital cost, maintenance cost, and total capacity of a landfill, the landfilling cost/tonne of MSW is calculated. Then, as per the amount of MSW available per day, the landfill avoided cost is computed (see supplementary material - **Appendix A**). The transport and landfill avoided costs per tonne of MSW are the same for all plants. In terms of avoided costs per day, these are highest for AD and compost compared to RDF, gasification and incineration, because compost and AD process a greater amount of given MSW than other technologies considered. The product value for each plant is calculated as per the amount and price of the product produced. Gasification due to more efficiency has the greatest product value followed by incineration, AD, compost and then RDF. The alternative potential value is the sum of avoided costs and product value higher for gasification, followed by incineration, AD, compost and RDF.

To estimate the cost of MSW processing, the alternative transportation cost has been initially estimated. Composting plant processes the same amount of MSW as AD but has higher alternative transportation costs due to greater plant distance. RDF, gasification, and incineration process the same amount of MSW but RDF has the lowest transportation cost, that is due to small distance of RDF plant. Similarly, AD has the lowest alternative transportation cost among all other technologies. Shredding costs are more for compost and AD than others due to the difference in the amount of MSW processed. The converting cost/tonne of MSW for each alternative is calculated as per capital cost, operating and maintenance cost, the life of the plant, and feedstock processing capacity. Then, as per the amount of MSW available per day for a particular technology, the processing cost per day is computed (see supplementary material - **Appendix A**). Converting cost is much higher for compost due to higher operating costs. AD is on second position as it processes a larger fraction of MSW than RDF, incineration, and gasification. Because of higher capital as well as operating and maintenance costs as compared to incineration and RDF gasification have higher converting costs. Incineration has lowest converting cost due to low capital investment and operating cost. For each alternative technique, the residue transportation and its landfill costs per day can be calculated as per the distance of landfill and amount of residue.

The AD, compost, and RDF have no waste product (ash); hence the residue for these plants is the MSW only which is not processed. Residue cost for compost and AD is the same because both have the same amount of rejected MSW. Gasification and incineration have some amount of waste product (ash) and the rejected MSW. Compared to all other plants, residue costs for gasification are more followed by incineration due to the addition of ash produced by the plants to the residue. Alternative total cost per day for each plant is summarized as alternative transportation, shredding, converting, and residual costs. Alternative total cost per day is highest for gasification and compost followed by RDF, AD and incineration. The difference between the total alternative potential value and total alternative cost depicts that gasification is more economically beneficial as compared to other technologies. The gasification, RDF, and incineration are processing same fraction and amount of MSW. Also, the alternative cost of RDF and incineration is lower than gasification but due to higher efficiency, gasification is more profitable than RDF and incineration. Similarly, compost can process the same amount of MSW that AD can but AD is more profitable than compost due to the difference between product, product value, and converting the cost of these technologies.

2.3.6 Environmental impact assessment and sensitivity analysis

The emissions are calculated for all technologies at each processing step like transportation, shredding, converting, and residue landfilling, as shown in Figure 2.2. Also, the avoided emissions are calculated for transportation, landfilling, and replacement of coal-based electricity and fertilizers. Detailed calculations are provided in the supplementary material. Sensitive parameters are recognized using sensitivity analysis. Here, the input parameters for sensitivity analysis focus on the collection efficiency, which is 65% for the selected region. The impact of a 20% increase (65-85%) in collection efficiency is evaluated for each category.

2.3.6.1 Global warming potential

A net reduction of 123 and 84 tonne CO_2 eq./day is obtained by AD and compost respectively, where RDF, incineration and gasification allows a reduction of 120, 51 and 62 tonne CO_2 eq./day. It can be observed from Figure 2.3 that AD has the highest reduction in GWP as compared to all other technologies. This is because of low greenhouse gases emissions during conversion process in AD. As compared to incineration and gasification RDF has larger reduction.

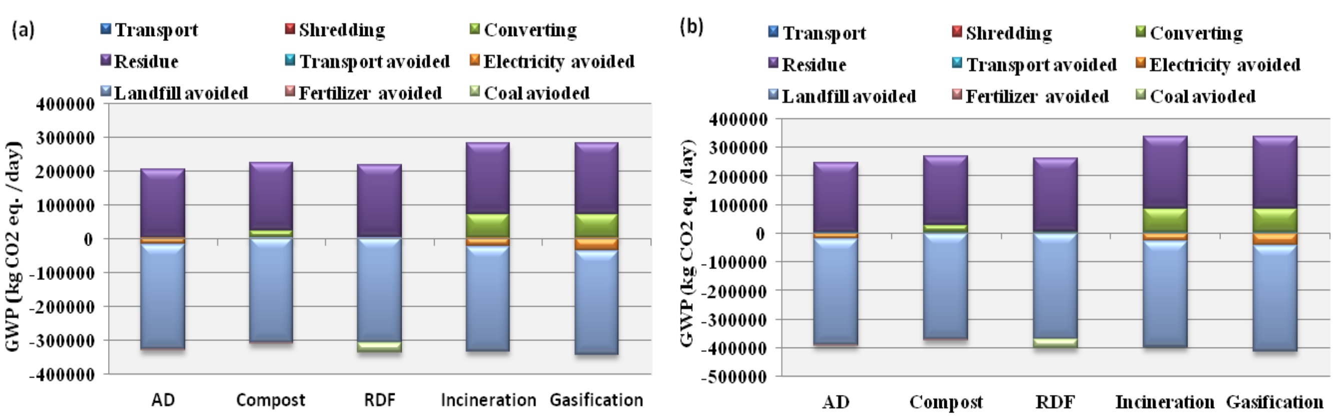

Figure 2.3: GWP impact of alternative technologies with collection efficiency (a) 65% (b) 85%

Converting emissions of gasification is almost equal to incineration, but it can reduce the GWP to a larger extent than incineration because of greater avoided grid emissions. Sensitivity analysis shows that 20% increase in collection efficiency enhances the net reduction up to 148, 102, 144, 61 and 75 tonne CO_2 eq./day through AD, compost, RDF, incineration and gasification.

2.3.6.2 Acidification Potential

AD and compost reduce the total SO_2 eq. by 112 and 32 kg/day. The AP benefits of RDF, incineration, and gasification are 180, 79, and 189 kg SO_2 eq./day, as shown in Figure 2.4. Gasification causes the highest reduction in AP among all the technologies, followed by RDF, AD, incineration and compost. Gasification has less converting acidifying emission compared to incineration while greater than RDF. But the avoided emissions of gasification are greater due to

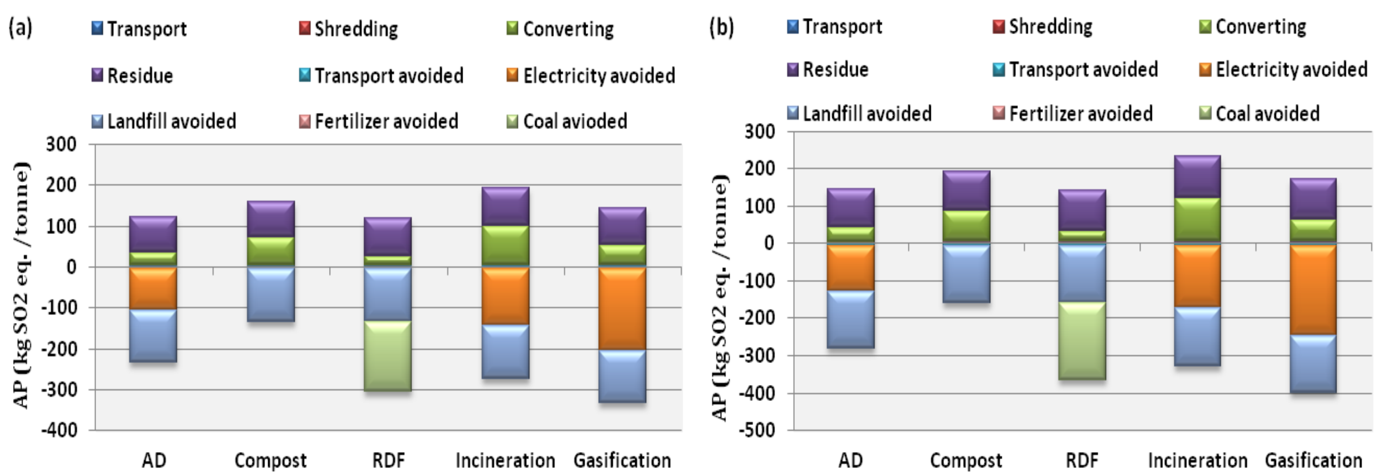

Figure 2.4: AP impact of alternative technologies with collection efficiency (a) 65% (b) 85%

more electricity generation as compared to other technologies. Similarly, AD has higher converting acidifying emissions than compost but can reduce the overall emissions to a larger extent by avoiding grid emissions. Sensitivity analysis shows that net reduction can be increased to 135, 31, 222, 95 and 227 kg SO_2 eq./day through AD, compost, RDF, incineration and gasification with 20% increment in collection efficiency.

2.3.6.3 Photochemical oxidation potential

AD and compost reduce 31 and 26 kg C_2H_4 eq./day. Reduction of total C_2H_4 eq. is obtained by RDF, incineration, and gasification is 32, 28 and 33 kg C_2H_4 eq./day. Figure 2.5 depicts the reduction tendency of gasification is highest. RDF lags gasification by a small value, whereas incineration lags AD. The performance of compost is also remarkable.

Gasification has slightly higher total emissions than AD and has more avoided emissions. AD and compost have similar total emissions, but AD is leading compost because of larger avoided emissions. Similarly, gasification and incineration have similar emissions, but net reduction is higher for gasification. Sensitivity analysis shows that a 20% increase in collection efficiency enhances the net reduction of 37, 32, 38, 34 and 40 kg C_2H_4 eq./day through AD, compost, RDF, incineration and gasification.

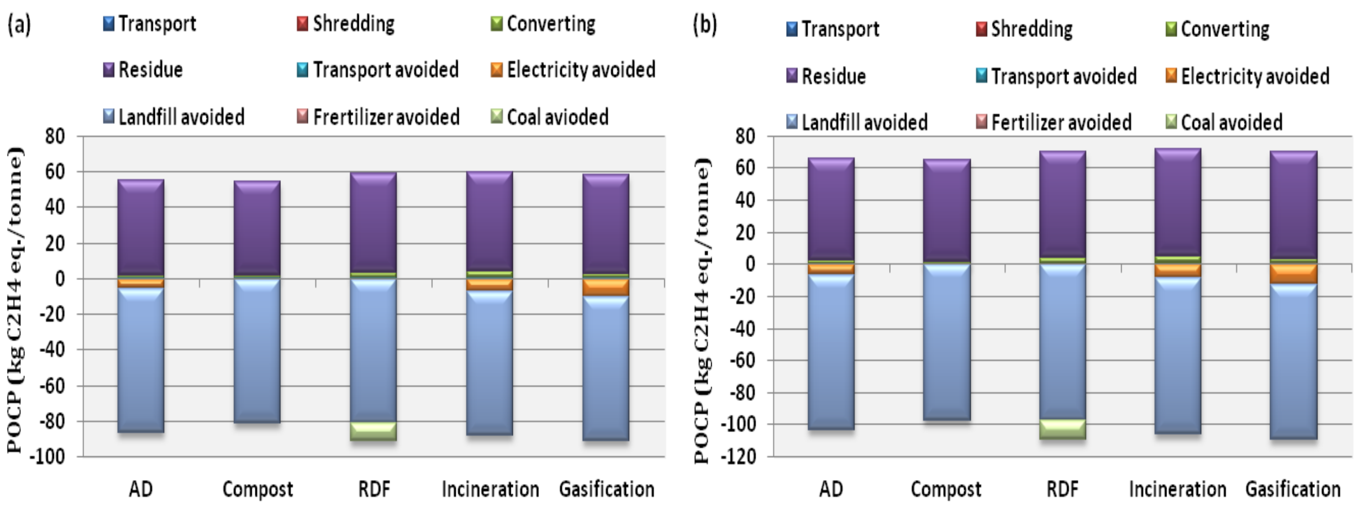

Figure 2.5: POCP impact of alternative technologies with collection efficiency (a) 65% (b) 85%

2.3.6.4 Eutrophication potential

The net reduction of 9.80 and 9.07 kg PO_4 eq./day is obtained by AD and compost, Whereas RDF, incineration, and gasification reduce 10.89, 4.52 , and 12.67 kg PO_4 eq./day. Gasification reduces the EP to the greatest amount, following RDF and AD. Incineration has the least reduction potential for eutrophication as shown in Figure 2.6.

Sensitivity analysis shows that net reduction can be increased to 11.90, 11.06, 13.07, 5.42 and 15.21 kg PO_4 eq./day through AD, compost, RDF, incineration and gasification with 20% increment in collection efficiency.

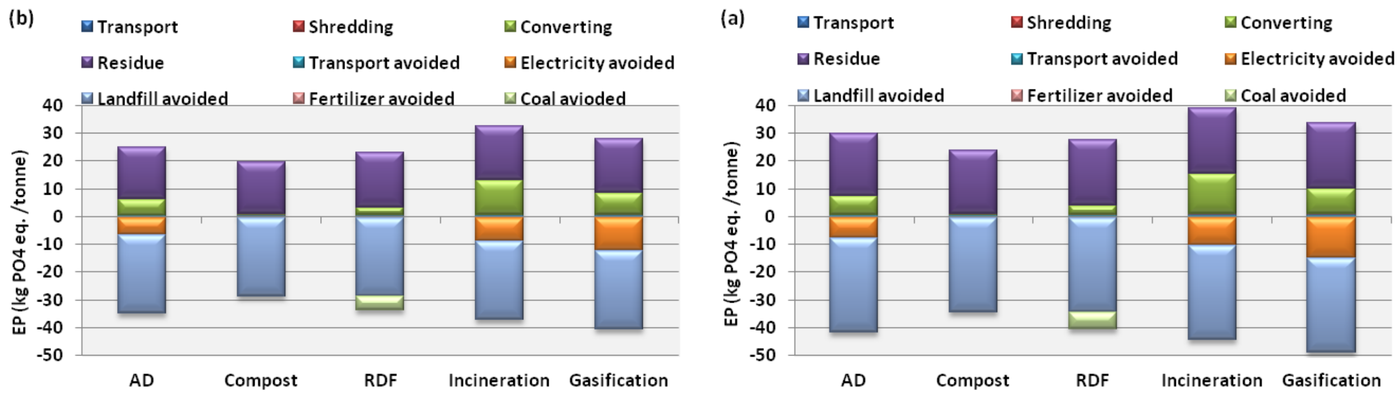

Figure 2.6: EP impact of alternative technologies with collection efficiency (a) 65% (b) 85%

2.3.7 Results and discussions of evaluation of MSW processing technologies

It has been found that processing MSW by AD is economically more profitable than composting and RDF. It can process 35% of the total MSW generated. AD is less profitable as compared to gasification and incineration. But it should also be noted that AD is processing food waste that is not suitable for gasification and incineration due to low CV and high moisture. Also, the portion of MSW given to gasification and incineration is not suitable for AD. Considering environmental releases, AD is best to improve both GWP and POCP by 123 tonne CO_2 eq./day and 31 kg C_2H_4 eq./day. Although in the case of AP and EP impacts, AD has a remarkable reduction of 112 kg SO_2 eq./day and 9.8 kg PO_4 eq./day. It can be concluded that AD is favorable in both economic and environmental terms to process the wet portion of MSW. Among all the alternatives in terms of economic factors, gasification is the best technology. It processes 31.7% of the total MSW and reduces the pollution for AP, POCP, and EP categories by 189 kg SO_2 eq./day, 41kg C_2H_4 eq./day, and 12.67 kg PO_4 eq./day. Also, for GWP it reduces 62 tonne CO_2 eq./day which is more than incineration. Gasification is found to be the most favorable technique to process the dry portion of MSW. The combination of AD and gasification gives the highest value for the difference of alternative potential value and alternative costs: INR 6.60×10^4 (USD 1.01×10^3)/day and the highest compared to any other combination. The combined operation can also reduce the environmental impact as GWP 186 tonne CO_2 eq. /day, AP 302 kg SO_2 eq./day, POCP 64 kg C_2H_4 eq./day and EP 22.48 kg PO_4 eq./day. This is highest as compared to any other combination and single technology. We can say that AD and gasification are preferable MSW processing techniques for the selected location and population. The integrated solid waste management system with a combination of AD and gasification will process the waste more efficiently with the best economic and environmental results. Sensitivity analysis shows that a 20% increase in collection efficiency reduces the environmental impact significantly for all the categories. Generally, MSW is considered a heterogeneous energy source with several characteristics varying depending on its origin from where it is collected. The percentage of various fractions (wet and dry matter) may vary for different locations and seasons. That further affects the efficiency and output of a plant. Similarly, the functioning of the plant is also sensitive to collection efficiency, the distance between landfill and processing plant, and Government policies. The above mentioned are the sensitive parameters that can influence the output of such plants in economic and environmental terms.

2.4 Evaluation of rice straw processing technologies

Figure 2.7 shows the rice straw utilization system. The geographical boundary is limited to Punjab, the foremost rice-producing state of India. As per ISO standards (ISO, 2006) and Renewable Energy Directive (RED, 2009), agricultural crop residues (rice straw) have zero lifecycle emissions till the collection stage. So, environmental impacts from crop growing part are not considered, and the system boundary starts from a collection of rice straw. The whole procedure comprises straw collection, bailing, transport, processing, and utilization of products produced. The biogas produced by the AD plant is further converted to electricity. The electricity and compost produced are assumed to replace coal-based grid electricity and chemical fertilizer emissions. Similarly, the production of ethanol will replace gasoline. Assuming that the plants consume carbon released during production in their next cultivation period, the biogenic CO_2 emissions from each stage of the life cycle are assumed to be neutral. The emissions from infrastructure and land usage are not considered in the present study.

Based on the methodology given in section 2.2, mathematical equations have been developed for the economic analysis of rice straw processing techniques. The total alternative cost of processing one tonne (A_{TCt}) of rice straw is calculated for each technology as per equation (2.7) which depends upon the feedstock cost, capital cost and running cost of the particular technology.

$$A_{TCt} = F_{Ct} + C_{Ct} + OM_{Ct} \quad (2.7)$$

Where F_{Ct} is the cost of feedstock per tonne (includes the cost of straw chopping, balling, storage and transportation), OM_{Ct} is operating and maintenance cost per tonne, C_{Ct} is plant capital cost per tonne that can be calculated as

$$C_{Ct} = \frac{C_{CT}}{\mathrm{T} \times 365 \times \mathrm{Fd}} \quad (2.8)$$

Where C_{CT} is the total capital cost of the plant, T is Life of the plant; F_d is the amount of feedstock processed per day. Further, OM_{Ct} is calculated as

$$OM_{Ct} = \frac{OM_{CY}}{365 \times \mathrm{Fd}} \quad (2.9)$$

Where OM_{CY} is operating and maintenance cost of plant per year.

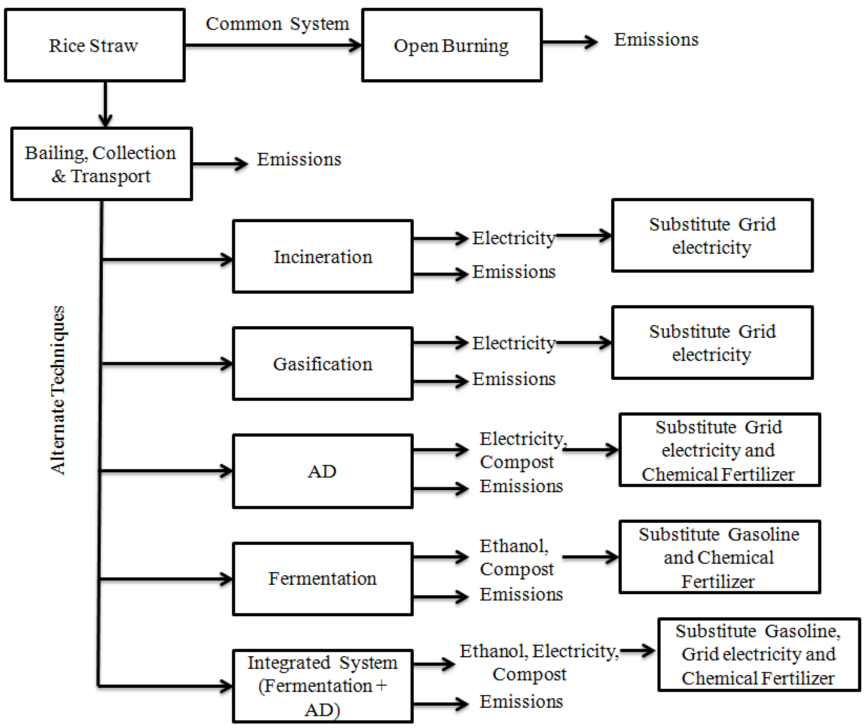

Figure 2.7: System boundaries adopted for the environmental assessment study

As per the amount of product produced and its economic value, the alternative potential value (A_{PVt}) is estimated as per equation (2.10) for each technique.

A_{PVt} = Amount of product produced × price of per unit product (2.10)

Finally, the net economic benefits are calculated as the difference of alternative potential value and alternative total cost, as per equation (2.11).

Economic benefit = $A_{PVt} - A_{TCt}$ (2.11)

2.4.1 Selected technologies and their characteristics assessment

This section gives the characteristics assessment of selected technologies and economic and environmental parameters in the India scenario. Emissions regarding the preparation of feedstock covering chopping, balling, and transportation of straw are calculated as per the information collected by visiting a straw collection center of a plant situated at Patiala. Straw chopping and baling by tractor consume 4.5 L and 3 L of diesel, respectively, for the one-acre land area. In the selected region, the straw yield is 24 quintals/acre (processed daytime). Transportation by tractor-trolley, having a capacity of 5.5 tonne consumes 5 L of diesel for 20 km (one side) in loaded and unloaded conditions. That gives the fuel consumption rate of 4 km/L. As per this information, diesel consumption in chopping, baling, and transportation (40 km round trip) is estimated and found 1.81 L/tonne. As per the utilization of diesel and emission factors for the vehicle [100] the emissions are estimated for one tonne of straw, as shown in Table 2.7. To calculate the avoided emissions for electricity, the emission factors for the Indian grid (coal-based) and open straw burning are taken from [83] and [153] as shown in Table 2.8. Avoided emissions by gasoline substitute are calculated by comparing the emissions by passenger car using 100% gasoline and 15% ethanol mix. The emission factor for the same is taken from [154] and presented in Table 2.9. The emission factor for gasoline production is adapted from [155] and shown in Table 2.9. The emission factor for chemical fertilizers is taken from [156]. The detailed calculations of each technology are given in supplementary material (**Appendix B**).

Table 2.7: Environmental emissions from the preparation of rice straw

Emission source	Pollutants (kg/tonne)					
	CO_2	CO	NO_X	SO_2	CH_4	PM
Straw chopping	0.24085	0.00237	0.00059	0.00065	0.00003	0.00009
Straw Baling	0.161	0.00158	0.0004	0.00043	0.00002	0.00006
Transportation	0.23312	0.00229	0.00057	0.00063	0.00003	0.00009
Total	0.63498	0.00626	0.00157	0.00172	0.00009	0.00024

2.4.1.1 Incineration

For electricity generation from rice straw, incineration technology-based plants are encouraged in some parts of the country. Punjab is being equipped with a maximum of straw-based power plants where 8 million tonne of straw is utilized. The Punjab Energy Development Agency mandated to consume 4.5 million tonne of straw from the total existing in 50 plants for generating 509.5 MW of power [83].

Table 2.8: Emissions from open field burning and coal-based electricity

Emission source	Pollutants					
	CO_2	CO	NO_X	SO_2	CH_4	PM
Open field burning (kg/tonne)	1460*	34.70	3.1	2	1.2	13
Coal based electricity (kg/kWh)	1.21	0.009	0.005	0.0075	0.03	0.002

* These CO_2 emissions are considered biogenic

Table 2.9: Emission factors for passenger cars using E-15 (15% ethanol mix with gasoline) and 100% gasoline along with gasoline production

Emissions	CO_2	CH_4	NO_X	CO	VOC	SO_2
E-15 (g/MJ)	69.7	0.01	0.19	1.19	0.25	NA
Gasoline (g/MJ)	73	0.02	0.6	13	1.5	NA
Gasoline Production (mg/MJ)	6000	--	16	0.63	190	6.5

Table 2.10: Environmental emissions of selected technologies

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	CH_4	VOC	PM	H_2S
Incineration	233.28*	0.5832	0.4536	25.92E-2	0.1944	--	--	--
Gasification	233.28*	0.66E-03	0.54	12.43E-3	5.74E-1	0.4001	2.87E-03	--
AD	2.0461*	0.6696	43.63E-3	0.4E-04	1.06646	0.0216	--	7.744E-03
Fermentation	68.9*	0.22048	0.1129	0.3026	0.00131	--	5.22E-02	--
Integrated operation	69.25*	0.3371	0.1205	0.3026	0.1871	0.0037	5.22E-02	1.35E-03

* These CO_2 emissions are considered biogenic

The largest plant of 12 MW near Ghanaur village in Patiala is working, which consumes 350 to 400 ton of straw per day [157]. The plant meets the electricity demand of nearby villages. This plant is visited and found that consuming 400 tonne/day of feedstock at a 90% capacity factor, it produces 648 kWh/tonne of electricity. After 12% internal consumption 570 kWh/tonne power is available for the grid. The monetary value of straw-based incineration power plants in India is INR 6.1 crore/MW (USD 0.93 million/MW), as shown in Table 2.11. Operating and maintenance cost is INR 47.26×10^5/year (USD 0.072 million/year) with an escalation rate of 5.72% per year and a plant life of 20 years [158]. The tariff rate is 7.88 INR/kWh (0.121USD/kWh) as provided by the Central Electricity Regulatory Commission, Government of India. Emissions for combustion technology are adopted from [84] for rice straw-fired boiler as given in kg/kWh and calculated for kg/tonne of straw, taking electricity potential of 648 kWh/tonne as shown in Table 2.10.

2.4.1.2 Gasification

The operational experience of a gasification plant working with a feedstock having a calorific value of 15 MJ/kg reported an efficiency of 18% in India [159]. Central Electricity Regulatory Commission (CERC) provides tariff rate of 7.20 INR/kWh (0.11USD/kWh) considering the capital cost of plant 5.9285 crore/MW (USD 0.912 million/MW) (after subsidy 4.4285 crore/MW or USD 0.681 million) [158] along with operating and maintenance cost of 49.97×10^5/year (USD 0.076 million/year) (escalation rate of 5.72%) for 20 years of plant life as shown in Table 2.11. The CO, VOC, and PM emissions for gasification are adopted from [160] as given in kg/GWh and calculated in kg/tonne taking a power potential of 777 kWh/tonne as calculated considering 18% efficiency. The CO_2 emission is considered as same as incineration technology because of the same carbon content of the feedstock. NO_X, SO_2, and CH_4 are taken from [161] as given in kg/GJ of biomass (agricultural residue) and calculated as kg/tonne of straw considering energy content of 15.54 GJ/tonne [162] as shown in Table 2.10.

2.4.1.3 Anaerobic digestion

India installed its first power plant capacity of 1MW, based on AD, using rice straw as feedstock in December 2011 at Fazilka (Punjab). It was designed to produce 12000 m^3/day of biogas to operate the power generation system for 24 hours at a capacity of 1MW from 40 tonne of rice straw. But due to a lack of biogas production, it can run only for four hours. With the efforts of the Indian Institute of Technology Delhi, now the plant can produce 3000 m^3/day of biogas from 10 tonne of straw and generate 6000 kWh by working 6 to 8 hours per day [163]. After 8%

internal consumption, 552 kWh/tonne of power is available for the grid. For such plants CERC provides tariff rate of 7.42 INR/kWh (USD 0.114/kWh) considering the capital cost of plant 11.85 crore/MW (USD 1.82 million/MW) (after subsidy 8.85 crore/MW or USD 1.36 million), along with operating and maintenance cost of 49.97×10^5/year (USD 0.076 million/year) (escalation rate of 5.72%) for 20 years of plant life [158] as shown in Table 2.11.

Table 2.11: Economic parameters of selected technologies in Indian scenario

Technology	Capital Cost	O & M cost	Plant Life (years)	Tariff	Electricity Potential (kWh/tonne)	Internal Consumption
Incineration	61.0 Million INR/MW	4726000 INR/year	20	7.88 INR/ kWh	648	12%
Gasification	44.285 Million INR/MW	4997000 INR/year	20	7.20 INR/ kWh	700	10%
AD	88.5764 Million INR/MW	4997000 INR/year	20	7.42 INR/ kWh	600	8%
Fermentation	350 Million INR/10 tpd	608.40 INR/tonne	30	39 INR/L	NA	NA

The emissions from the AD are calculated as per biogas production and its utilization in biogas engines are presented in Table 2.10. In the case of production of biogas, the emissions are calculated considering 1% leakage of biogas [164], taking biogas yield of straw 300 m^3/tonne [163]. Biogas engine emissions are calculated as per the information adopted from [128] in gram/GJ of electricity produced and calculated as kg/tonne of straw, considering the energy content of electricity at 3.6 MJ/kWh and power potential as 600 kWh/tonne.

2.4.1.4 Fermentation

Various countries are producing ethanol from sugar crops (like sugarcane) and starch crops (like maize and wheat) on a large scale. The biomass is ground down, and starch converted to sugar by enzymes and then converted to ethanol [145]. Bioethanol can be obtained from agricultural waste products like rice straw, peel of fruits, corn cobs and potatoes [165]. Carbohydrates are the major component of such wastes that can be fermented and converted into alcohol. 41%-46% alcohol can be obtained from different fermentation materials [166].

In India, the commercial production of ethanol from agro-waste is not started. However, much industry research and development are established with the efforts of the Biochemical Engineering Research Centre, IIT Delhi. In 1980, an integrated bioprocess demonstration plant was implemented to produce 50 L of bio-ethanol per day. The facility reported the ethanol yield of rice straw at 230 L/ton. Nowadays, in India, various labs are involved in Research and Development to produce ethanol from agricultural wastes. National Institute for Interdisciplinary Science and Technology (NIIST) campus setups a pilot plant of capacity 50 kg/day [167]. The Indian Oil Corporation Limited has established a pilot plant at Faridabad of capacity 250 kg/day and reported ethanol yield of 239 and 253 L/tonne of rice straw using pre-treatment technologies of dilute acid and steam explosion [81]. The world's first sweet sorghum-based ethanol production distillery was started in India Andhra Pradesh, in 2007 [168].

Recently, in 2016 Indian Government invested 35 crores (USD 5.38 million) in Kashipur Uttarakhand to establish a second-generation ethanol plant. This demonstration plant can process 10 tonne of agriculture waste (rice, wheat and sugarcane straws) per day and produces 300 L ethanol/tonne [169]. The ethanol yield of rice straw alone is reported 260 L/tonne [82]. As per the lower heating value of ethanol and gasoline, 21.2 and 32.4 MJ/L, respectively, the ethanol obtained from one tonne of straw can replace 170 L of gasoline [78]. The Cabinet Committee on Economic Affairs government of India has revised the price of ethanol from INR 49.50 to 39/L [170] as shown in Table 2.11. The ethanol production cost is calculated as 36.49 INR/ L (0.56 USD/L) (calculation given in supplementary data). Emissions for fermentation are adopted from [78] in kg/MJ and calculated as kg/tonne of straw taking energy content of ethanol 21.2 MJ/L [171] and ethanol yield 260 L/tonne as presented in Table 2.10.

2.4.1.5 Integrated operation of AD and fermentation

Production of ethanol by fermentation provides the waste called stillage that can be anaerobically digested to produce biogas [172]. Biogas produced is used as a fuel to generate electricity and steam. Each liter of ethanol production provides 5-10 L of stillage with 0.8 kg of total solids [173]. With ethanol yields of 260 L/tonne of straw, the stillage available in terms of total solids is 208 kg/tonne of straw [82]. Biogas that consists of 60% methane with a density of 1.217 kg/m^3 and energy content of 22 MJ/m^3 can be recovered by AD of the stillage. A net 6.36 MJ biogas per liter of ethanol is available to produce electricity. After fulfilling the heating requirements of the plant the 0.37 kWh/L of ethanol is surplus that can be sold to the grid [82]. The integrated operation of fermentation and AD to process rice straw do not exist in India. The economic parameters related to fermentation are taken the same as discussed in section (2.4.1.4). For AD plant the cost of feedstock is not applicable because stillage is available within the plant as waste material. The total alternative cost for AD is calculated for 208 kg of feedstock as per the information provided in section (2.4.1.3). The alternative potential value for AD is calculated as per surplus electricity potential of 0.37 kWh/L of ethanol or 96.2 kWh/tonne of straw (taking ethanol yield 260 L/tonne of straw) at tariff rate 7.42 INR/kWh. Like economic parameters, environmental emissions are the same for fermentation plants, as discussed in section (2.4.1.4). As per the information imparted in the section (2.4.1.3), the environmental emissions for AD are estimated by calculating emission per unit of electricity and then for per tonne of straw, considering the electric potential of 96.2 kWh/tonne as shown in Table 2.10.

2.4.2 Economic analysis

Economic analyses of selected technologies are presented in Table 2.12. The feedstock cost that consists of rice straw chopping, bailing, transportation and storage cost per tonne is same for all the proficiencies. This cost is taken as per the instructions provided by the CERC Government of India [158]. The capital cost of processing per unit tonne of rice straw is highest for integrated operation, followed by fermentation, AD, incineration, and gasification. Gasification has less capital cost even as compared to incineration, which is imputable to the subsidy provided by the Government. Among all the technologies, fermentation has the highest operation and maintenance cost due to the plant's heat and electricity requirements. The steam and electricity cost contributes to INR 1.00/L and INR 0.59/L of ethanol (see supplementary information - **Appendix B**).

Interestingly the integrated operation shows less operating and maintenance costs among all the plants. Because in this system, the biogas produced by AD is sufficient to fulfill the steam and electricity requirements. Also, the stillage produced from fermentation is used as feedstock for AD plant and hence saves the feedstock cost for AD. This reduction of steam, electricity and feedstock costs in the overall process is a significant economic benefit of an integrated operation. After fermentation, the gasification has the greatest operating and maintenance cost followed by incineration and AD.

Table 2.12: Economic analysis of selected technologies

		Incineration	Gasification	AD	Fermentation	Integrated
Feedstock cost (INR/tonne)		3342	3342	3342	3342	3342
Capital cost (INR/tonne)		250	202.21	303	5538	5601
Operating and Maintenance cost (INR/tonne)		388	456.34	342	608	266
Alternative total cost (INR/tonne)		3981	4001	3988	9490	9209
Product produced/ tonne	Electricity (kWh)	570	630	552	--	96.2
	Ethanol (L)	--	--	--	260 L	260 L
	Compost (kg)	--	--	50 kg	208 kg	10.04 kg
Economic value of product per unit (INR)		7.88/kWh	7.20/kWh	7.42/kWh +1.2/kg	39/L +1.2/kg	39/L+7.42/ kWh +1.2/kg
Alternative potential value (INR/tonne)		4491	4536	4155	10389	10735
Economic Benefit (INR/tonne)		510	534	167	899	1525

The total alternative cost, which is the summation of feedstock price, capital cost, and operating and maintenance cost, is the highest for fermentation technology. Due to savings in operating and maintenance costs, the integrated operation shows a remarkable reduction in total alternative costs compared to fermentation alone. The plant gasification, AD and incineration show a difference of the small fraction in total alternative cost. Also, the total alternative cost of these technologies is less than half of the fermentation and integrated operation. Due to more efficiency, gasification produces more electricity than incineration and AD. Along with electricity, AD also produces compost similarly; along with ethanol, the fermentation also produces compost. The integrated operation provides three types of products, ethanol, electricity, and compost, among all the technologies.

The incineration, gasification, and AD produce electricity as a product. Still, the per-unit economic value of electricity is highest for incineration, followed by AD and gasification, because of the difference in Government policies for these plants. The alternative potential value is highest for integrated operation among all due to the benefit of the production of three types of products. Fermentation is in the second spot in the case of alternative potential value. Still, the per-unit product value for gasification is less than incineration and AD. Still, on the other hand, because of more efficiency, its alternative potential value is more significant than incineration and AD. The economic benefit, i.e., the difference in total alternative cost and alternative potential value, depicts that integrated operation is economically more beneficial than other technologies. Fermentation is in second place, followed by gasification, incineration, and AD. The AD shows positive economic benefit, but the same is significantly less than other technologies due to less electricity produced than others.

2.4.3 Environmental analysis

The emissions are calculated for all technologies at each step of processing, as shown in Figure 2.7. Also, the avoided emissions are calculated for transportation, landfilling, and replacement of coal-based electricity and fertilizers. Detailed calculations are provided in the supplementary material. Here, the input parameters for sensitivity analysis focus on the efficiency of the particular technology. The impact of a 5% increase in efficiency is evaluated for each environmental impact category as a sample case.

2.4.3.1 Global warming potential

A net reduction of 1220 and 1343 kg CO_2 eq./tonne is obtained by incineration and gasification, as shown in Figure 2.8. AD, fermentation, and integrated operation reduce 1162, 152, and 288 kg CO_2 eq./tonne. Gasification has the highest reduction in GWP because its processing emissions are less than incineration and AD. Also, its avoided emissions are highest in comparison to all other technologies due to more efficiency and electricity generation potential. Incineration lacks gasification and leads AD by a small fraction due to the difference of avoided emissions, which is further related to efficiency. Fermentation and integrated operation have a remarkable reduction in GWP but less than other technologies.

However, the processing emissions of these technologies are less than all other technologies, but avoided emissions are much less than others. The integrated operation has more reduction potential than fermentation because of the grid and fertilizer emissions reduction. Sensitivity analysis indicates that a 5% growth in efficiency enhances the net reduction up to 1276, 1405, 1219, 164 and 355 kg CO_2 eq./tonne through incineration, gasification, AD, fermentation and integrated system.

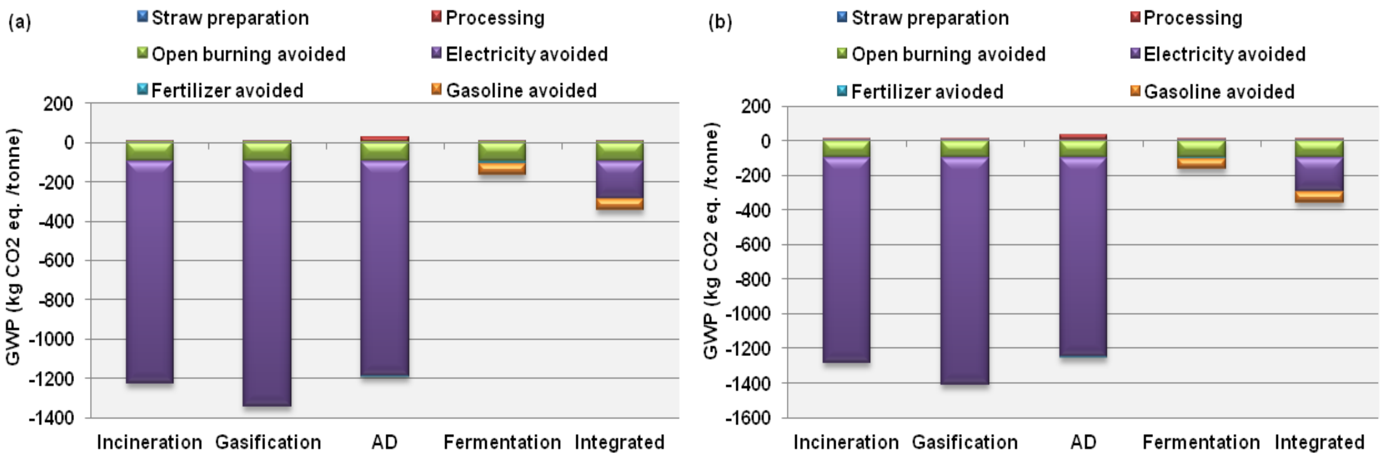

Figure 2.8: GWP impact of selected technologies with efficiency (a) Practical (b) 5% increment

2.4.3.2 Acidification potential

As depicted in Figure 2.9, incineration and gasification reduce the total SO_2 eq. by 10.09 and 10.70 kg/tonne. The AP benefits of AD, fermentation, and integrated operation are 10.19, 5.53 and 6.53 kg SO_2 eq. respectively. The fermentation and integrated operation have a significant reduction in environmental impact for this category but lack from incineration, gasification and AD. The processing emissions of all the technologies are almost equal except for AD, which has the least processing emission for this category. The technologies that generate electricity show leading results for AP due to substitute to grid electricity. Due to the same reason gasification is leading all. Sensitivity analysis shows that net reduction can be increased to 10.40, 11.05, 10.51, 5.62 and 6.61 kg SO_2 eq./tonne through incineration, gasification, AD, fermentation and integrated system with 5% increment in efficiency.

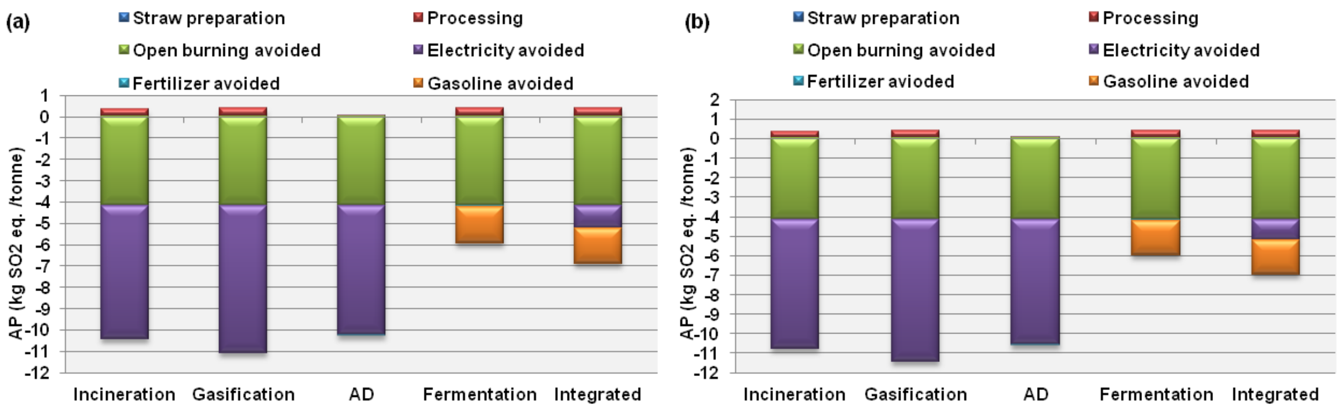

Figure 2.9: AP impact of selected technologies with efficiency (a) Practical (b) 5% increment

2.4.3.3 Photochemical oxidation potential

Incineration and gasification reduce 1.33 and 1.14 kg C_2H_4 eq./tonne respectively. Reduction of total C_2H_4 eq. is obtained by the AD, fermentation and integrated operation are 1.31, 2.85 and 2.90 kg C_2H_4 eq./tonne as shown in Figure 2.10.

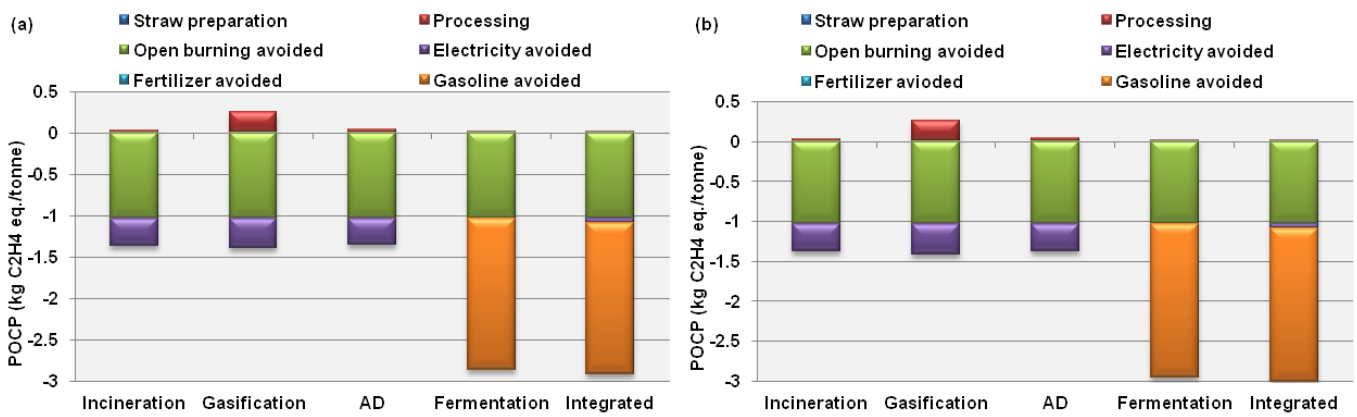

Figure 2.10: POCP impact of selected technologies with efficiency (a) Practical (b) 5% increment

Here fermentation and integrated operation lead the all other technologies because of high reduction in POCP due to gasoline substitute. Also, both the technologies have low processing emissions compared to the other. Integrated operation leads to fermentation because gasoline substitution also replaces coal-based electricity. Among incineration, gasification, and AD, the gasification lacks a tiny fraction due to more processing emissions that are greater by small value than others. This small difference is further related to the difference in VOC emissions during processing, which is more for gasification. Sensitivity analysis indicates that a 5% increase in efficiency, enhances the net reduction up to 1.34, 1.15, 1.33, 2.94 and 3.0 kg C_2H_4 eq./tonne through incineration, gasification, AD, fermentation and integrated operation.

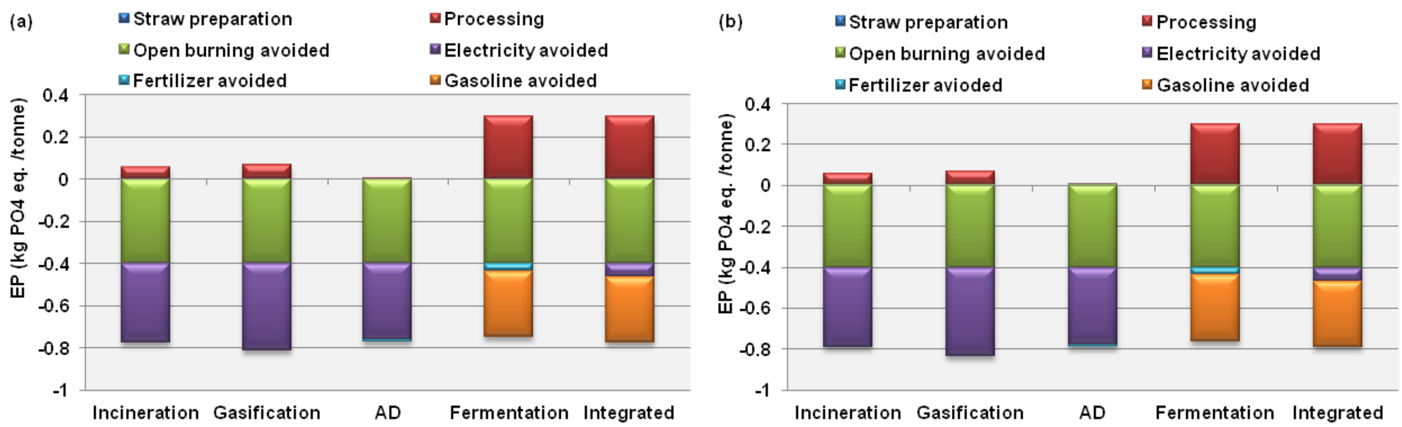

Figure 2.11: EP impact of selected technologies with efficiency (a) Practical (b) 5% increment

2.4.3.4 Eutrophication potential

The enrichment of water sources due to chemical nutrients is called eutrophication. It enhances the production of algae and aquatic plants. Eutrophication potential is calculated as a PO_4 equivalent for all emissions contributing to this category. According to Figure 2.11, the net reduction of 0.71 and 0.74 kg PO_4 eq./tonne is obtained by incineration and gasification. Whereas AD, fermentation and integrated operation reduce 0.75, 0.44 and 0.47 kg PO_4 eq./tonne respectively. Due to less processing emissions, AD has the highest reduction in EP compared to all other technologies. Gasification is in second place because of low processing emissions and high reduction due to grid electricity substitution. In the case of fermentation and integrated operation, the gasoline substitution benefit is almost equivalent to electricity substitution by all other technologies. But fermentation and integrated operation are lacking compared to other technologies due to high processing emissions. This is further related to COD emission that is greater for these two technologies as compared to others. However, both the technologies have a significant reduction in EP environmental impact. Sensitivity analysis indicates that net reduction can be increased to 0.73, 0.76, 0.78, 0.46 and 0.49 kg PO_4 eq./tonne through incineration, gasification, AD, fermentation and integrated system with 5% increment in efficiency.

2.4.4 Results and discussions of evaluation of rice straw processing technologies

Various technologies are evaluated thoroughly in terms of their economic and environmental impacts. The analysis clears the picture about the benefits and drawbacks of one and the other technologies. Results show that the integrated operation of fermentation and AD is economically more profitable to swear out the rice straw compared to all other selected technologies. Fermentation found to be more profitable as compared to incineration, gasification and AD. It indicates that the production of bioethanol is economically more beneficial as compared to electricity generation. If we compare the technologies only for electricity generation, then gasification is found to be more profitable than incineration and AD. The AD is lacking as compared to other technologies due to low efficiency.

For environmental evaluation, all the technologies are ranked on the basis of their environmental impact reduction potential for each category, as presented in Table 2.13. The analysis shows that gasification is best to improve the overall environmental impact. It is ranked first to improve the GWP and AP, and second and fifth to improve EP and POCP as shown in Table 2.13.

Table 2.13: Ranking of selected technologies on the basis of environmental impact for each category

Technology	GWP	AP	POCP	EP
Incineration	2	3	3	3
Gasification	1	1	5	2
AD	3	2	4	1
Fermentation	5	5	2	5
Integrated	4	4	1	4

The coal-based electricity has large CO_2 and CH_4 emissions that mainly contribute to global warming. Due to more electricity generation potential, gasification replaces these emissions to a greater extent in comparison to other technologies, hence shows the best results for this category. Similarly due to the replacement of SO_2 and NO_X that mainly contribute to AP category gasification is best among all systems. Production of ethanol by fermentation and integrated operation give best results to reduce the POCP as compared to electricity generated by incineration, gasification and AD. That is due to low processing emissions and the replacement of gasoline in which CO emissions are more, which mainly contribute to the POCP category.

For GWP, AP and EP, the electricity generation leads to ethanol production for environmental categories. However, for all the environmental impact categories, ethanol production has a remarkable reduction. In the case of ethanol production, the integrated operation gives the best results for all the environmental impact categories compared to fermentation. We can conclude that the integrated operation of fermentation and AD is best for processing rice straw compared to all the technologies. Along with the remarkable reduction in environmental emissions, it has economic benefits that are reasonably greater than all other technologies. Gasification is best to reduce overall environmental impact and the sensible economic benefit that is less than fermentation and integrated operation but greater than incineration and AD. Sensitivity analysis indicates that a 5% growth in efficiency reduces the environmental impact significantly for all the categories.

2.5 Chapter summary

This research concludes that industrial ecology is an efficient approach to comparing the pros and cons of various waste processing technologies. The combination of LCA and Industrial ecology provides the economic and environmental evaluation simultaneously. It makes it easy to judge how a community's waste aligns with the technology. In this research work, the AD and gasification are indicated as the preferred technologies for processing the wet and dry portion of MSW, respectively in the Indian scenario. The combination of both the technologies is found to be economically most optimum and environment friendly. In the proposed research, for a population size of 0.1 million, AD and gasification shows a potential economic value of 1.91×10^4 INR/day and 4.70×10^4 INR/day, respectively. The processing of food waste by AD shows a remarkable reduction in environmental emissions for categories; GWP, AP, POCP and EP by 123 tonne CO_2 eq./day, 112 kg SO_2 eq./day, 31 kg C_2H_4 eq./day and 9.80 kg PO_4 eq./day respectively. Whereas the processing of dry waste by gasification shows a remarkable reduction in environmental emissions for categories; GWP, AP, POCP and EP by 62 tonne CO_2 eq./day, 189 kg SO_2 eq./day, 33 kg C_2H_4 eq./day and 12.67 kg PO_4 eq./day respectively.

In case of rice straw, the production of ethanol by the integrated operation is indicated as preferred technology as compared to all other selected technologies by this study. This research indicates that the integrated operation of AD and fermentation shows economic benefits of 1525 INR /tonne and a significant reduction in environmental emissions. For electricity production, gasification is more preferable than incineration and AD both in economic and environmental terms with an economic benefit of 534 INR/day. The use of surplus rice straw and MSW for energy production can contribute to the sustainable growth of a country. As a building block of the theoretical aspects, the economy and environmental factors are analyzed that can add a legitimate contribution based on waste management and waste to energy generation systems. Further, the study conceptualizes biomass (MSW and rice straw) based microgrids selecting the best technologies from this comparative analysis.

CHAPTER 3

Conceptualization and evaluation of municipal solid waste and rice straw based microgrid

3.1 Introduction

The comparative evaluation of various MSW processing technologies presented in chapter 2 reports that AD and gasification are the most prominent techniques for processing the dry and wet types of waste. In the case of rice straw for electricity production, gasification is reported as the most well-known technique. This chapter proposes the conceptualization of MSW and rice straw-based small-scale microgrids considering different case studies. The reported best techniques are selected for a particular feedstock to design a microgrid. In the case of MSW, the city named Nabha and its nearby village Duladi are considered and presented in section 3.2. The proposed microgrid is capable of processing the urban waste of a city with a 0.1 million population and fulfilling the electricity demand of a nearby village with 225 houses. The microgrid consists of MSW processing techniques: AD (processes a wet portion of MSW) and gasification (processes a dry portion of MSW) that are further integrated with solar, battery, and the main grid. The landfill avoided cost is also calculated along with the waste processing cost. In the case of rice straw selecting gasification technique, a small-scale microgrid is proposed for the village Mallehwal and discussed in section 3.3. The gasification technique that processes rice straw to produce electricity is further integrated with solar, battery, and the utility grid. This microgrid can process the surplus rice straw of the village has 250 houses and 900 acres of cultivated land. The system processes 1128 tonne/year of surplus rice straw and meets the same village's load demand.

The modelling and simulation of both systems are done using Matlab software. The size of the microgrids is optimized using an ABC algorithm. The effectiveness of the adopted technique is verified by comparing the results with PSO algorithm. The economic evaluation of the proposed systems is done on the basis of NPC, ASC and LCOE. The environmental impact of proposed microgrids is also evaluated using LCA methodology. The presented study could act as a source of technological information that further shows a new way to utilize waste in a hybrid electricity generation system. The outcomes of the proposed work may influence the decision and policy-making related to waste-to-energy projects for a particular country.

3.2 Conceptualization and evaluation of MSW based microgrid

To estimate the amount and type of waste, along with the village's load demand, the Indian state, Punjab, is selected. For this work, the city named Nabha and its nearby village Duladi, which is also very close to the city's dump site, are considered. The microgrid is proposed to process the MSW of this small city with a population size of 0.1 million and fulfill the electricity demand of a nearby village comprising 225 houses with 8.58×10^5 kWh of electricity demand per annum. The characterization of the waste is done because of four seasons, i.e., summer, spring, autumn, and winter throughout the year. MSW samples are taken from collected waste for the respected seasons and then analyzed for physical characterization, as shown in Figure 3.1. The amount of food and vegetable 35%, paper 3.2%, rags 12.3%, rubber 0.5%, glass 0.1%, plastic 6.5%, leaves and straw 12.4%, inerts 28% and metals 0.8% are estimated from mixed waste. Two streamlines, wet and dry, are followed to process the collected waste.

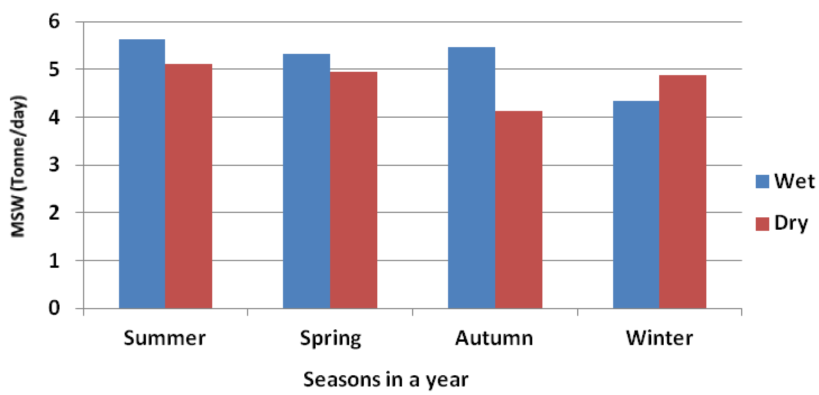

Figure 3.1: Variation of waste in different seasons

The wet stream includes the biodegradable portion, and dry stream takes rags, plastic, rubber, leaves, and straw. Due to the deforestation effect, the waste paper is not selected for processing by any means though recycling is the best method to utilize waste paper. The per capita waste generation rate and collection efficiency are also estimated from the existing MSW collecting system of the city's municipal corporation authority. The city has a per capita waste generation rate of 0.252 kg per day and a collection efficiency of 65%. The amount of waste (wet and dry) generated per day is highest in summer, as given in Figure 3.1.

Compared to summer, the wet portion of waste decreases by 2% in spring, 1% in autumn, and 8% in winter. Similarly, the dry portion is decreased by 1% in spring, 6% in autumn, and 1% in winter. From a population size of 0.1 million, a net 25.20 tonne/day (in summer) of waste is generated. With a collection efficiency of 65%, 16.38 tonne/day is available to process.

Table 3.1: Load profile of selected village (225 houses)

Sr. No.	Type of Load	Quantity	Rating (Watt)	Summer (Mar-Oct)		Winter (Nov-Feb)	
				Hrs/Day	Watt-Hrs/Day	Hrs/Day	Watt-Hrs/Day
	(1) Domestic load demand						
1	CFL	5	27	4	540	3.5	472.5
2	LED	4	18	10	720	9.5	684
3	Ceiling Fan	5	80	9	3600	0	0
4	Exhaust Fan	2	40	1	80	1	80
5	Television	1	100	9	900	9	900
6	Cooler	2	200	10	4000	0	0
7	Submersible Pump	1	745	0.25	186.25	0.25	186.25
8	Computer	1	300	3	900	5	1500
9	Room Heater	2	150	0	0	6	1800
10	Water Heater	1	2000	0	0	1	2000
	Total one house				10926.25		7622.75
	Total kWh/Day				10.92625		7.62275
	Total for 225 houses kWh/Day				2457		1714.5
	(2) Community load demand						
1	Shops	9	400	11	10575	11	10575
2	Small Industry	2	5000	8	80000	8	80000
3	School	1	5000	8	40000	8	40000
4	Street Lights	20	30	9	5400	12	7200
	Total				135975		137775
	Total kWh/Day				135.975		137.775
	Total Demand (1)+(2) kWh/Day				2592.75		1852.27

The selected village with 225 houses has a peak load demand of 215 kWh and a load factor of 0.455, respectively. For two seasons' summer (March to October) and winter (November to February), different load profiles are considered in Figure 3.2. Table 3.1 shows the detailed load demand of a village with 225 houses. The selected site has good solar asses of average 5.76kWh/m^2 per day. Figure 3.2 shows the hourly solar radiation of the selected site for the year.

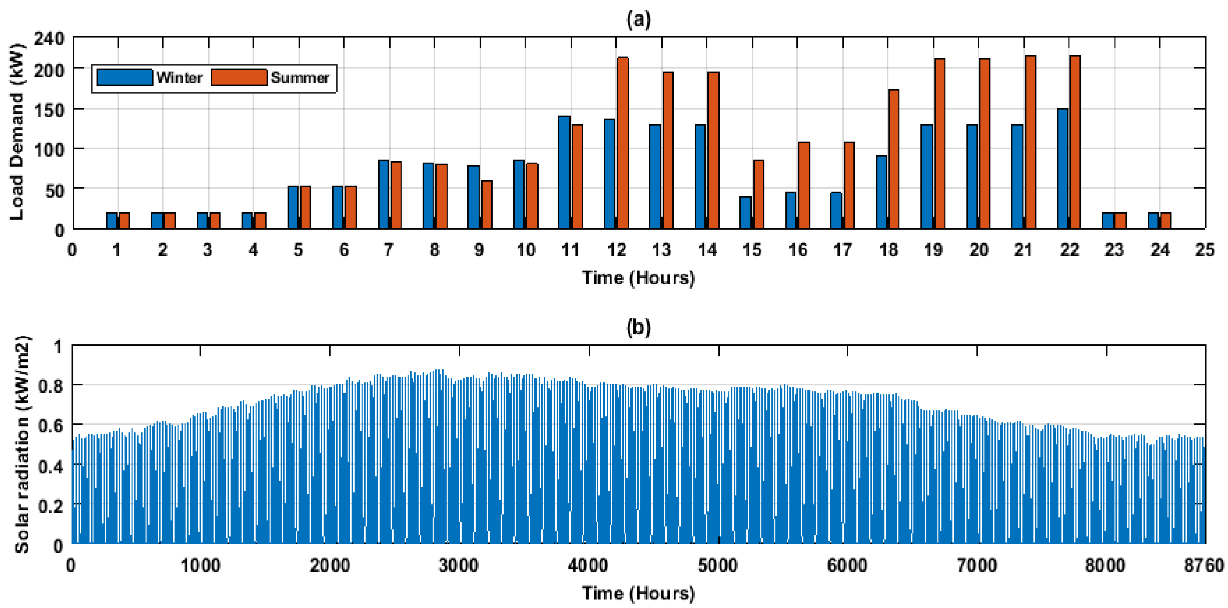

Figure 3.2: (a) Daily load demand of village (b) Solar radiation at the selected site

3.2.1 System description of MSW based microgrid

In the proposed system, the processing of dry and wet waste is kept on priority. The technologies AD and gasification are selected to process waste's wet and dry portions, respectively. As per the total collected waste, fraction of wet and dry wastes, and seasonal variations, two supply chains are made for both technologies. Segregation of waste is assumed to be done at the collection end with community participation. This is the most economical way to segregate the waste; however, poor segregation may result in a 17% rejection rate in segregated waste [174]. In the present case, the total waste generated as per the collection efficiency, fraction of wet and dry waste in summer, 17% rejection rate due to poor segregation, a net amount of wet waste of 5.63 tonne/day, and dry waste of 5.15 tonne/day are available. This amount of wet and dry waste is sufficient to run AD and gasifier plants of 32 kW and 64 kW considering the 80% capacity utilization factor (CUF). These capacities are calculated as per the electricity generation potential of AD (110 kWh/tonne) and gasifier (240 kWh/tonne) technologies for Indian MSW [175].

The total waste generated by the selected population size is not enough to supply the particular load. Also, the seasonal variation in MSW generation will disturb the feedstock supply chain. So, to meet the total load demand and make the system more reliable, solar and battery storage systems are used to make a hybrid system. Different components of the proposed microgrid are shown in Figure 3.3.

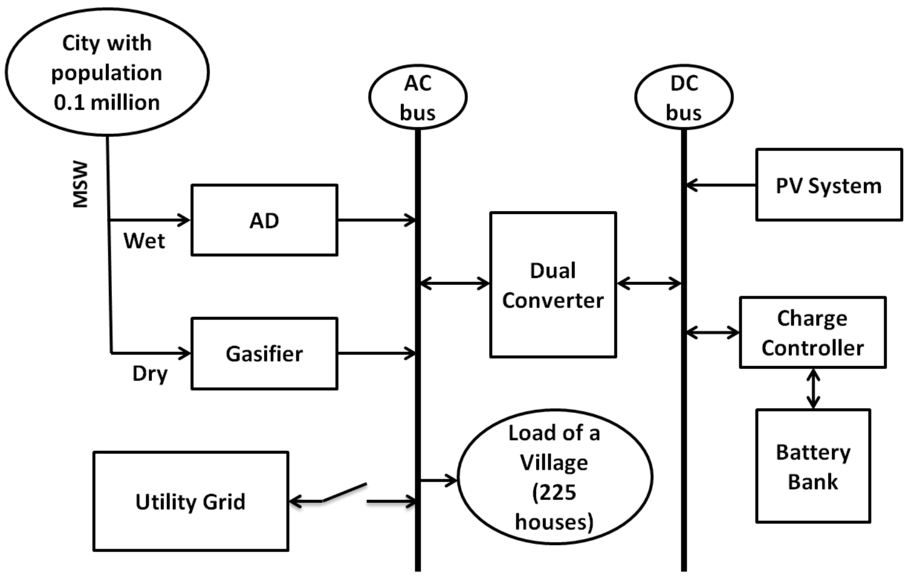

Figure 3.3: Various components of the proposed microgrid

AD and gasifier technologies generating electricity from MSW are connected to the AC bus and the load. A Solar and battery storage system is also integrated to make it reliable and connected to the DC bus. A dual converter is used to connect the AC and DC bus. A charge controller is used to limit the discharging and charging rate of batteries and sustain the smooth flow of electricity. The proposed microgrid is also connected to the utility grid so that excess power can be sent to the utility, and in crisis, power can be drawn from the grid. The capacity of AD and gasifier is kept as per the available amount of waste. The capacity of the PV and battery system is set up using the optimization of the whole system to meet the load demand in islanded mode with minimum overall system cost.

3.2.2 Mathematical modelling of the proposed MSW based microgrid

The numerical modelling of the system mechanism is discussed as follows.

3.2.2.1 Anaerobic digestion

The biogas generation yield of present wet MSW is 55 m^3/tonne and 2 kWh of useable electricity can be produced from 1m^3 of biogas with 60% methane [175]. For the present case 110 kWh of electricity can be produced from one tonne of wet MSW with biogas to the electricity conversion efficiency of 33.5%. The CV of biogas with 60% methane is 36.3 MJ/m^3.

The amount of biogas production (m^3/hour) is calculated as [176]

$$Q(t) = B_{bg}(t) \times B_{pp} \tag{3.1}$$

where, B_{bg}(t) is the amount of biomass and B_{pp} is biogas production potential of biomass (55 m^3/tonne)

The lower heating value of biogas LHV is calculated as [176]

$$LHV = \left(\left(P_{CH_4}/100\right) \times LHV_{CH_4}\right) \tag{3.2}$$

where, P_{CH_4} is the percentage of methane in biogas (60%) and LHV_{CH_4} is lower heating value of methane (36.3 MJ/m^3 or 10 kWh/m^3).The output of biogas system P_{bio} (kWh/hour) is calculated as [176]

$$P_{bio}(t) = (\eta_{bio} \times Q(t) \times LHV) \tag{3.3}$$

where, η_{bio} is electrical conversion efficiency (from biogas to electricity).

The maximum installed capacity of the AD plant (P_{bio_max}) is calculated as per the amount of wet waste available per day in the summer season, that is 5.63 tonne/day, using the equation given below:

$$P_{bio\_max} = \frac{(B_{bg} \times B_{pp})\left(\left(P_{CH_4}/100\right) \times LHV_{CH_4}\right) \times \eta_{bio}}{(24 \times CUF)} \tag{3.4}$$

3.2.2.2 Gasification

The maximum installed capacity of the gasifier system (P_{gasi_max}) is obtained as per the amount of waste available per day in the summer season, which is 5.15 tonne/day as follows [177]

$$P_{gasi\_max} = \frac{B_{bmg} \times 1000 \times CV_{bmg} \times \eta_{bmg}}{3.6 \times 24 \times CUF} \tag{3.5}$$

where B_{bmg} is the amount of biomass available (tonne/day), CV_{bmg} is the calorific value of dry waste (3.27 MJ/kg), η_{bmg} is biomass to electricity conversion efficiency of gasifier (20%), CUF (80%). The per-hour output of the gasifier can be obtained as

$$P_{gasi}(t) = \frac{B_{bmg}(t)\times 1000\times CV_{bmg}\times \eta_{bmg}}{3.6} \quad (3.6)$$

3.2.2.3 Solar PV System

For a particular location output power of a PV system (P_{sol}) depend on a solar intensity that can be calculated as [178]

$$P_{sol}(t) = P_r \times F_{loss} \times \frac{\mathrm{Gh(t)}}{\mathrm{Gs}} \quad (3.7)$$

where, P_r is the power rating of the single PV panel, F_{loss} is the loss or derating factor (due to temperature, dust, and shadow effects), $\mathrm{Gh(t)}$ is the solar radiation (W/m^2) at any time (t), and Gs is the standard solar incident radiation (1000 W/m^2). In this study temperature effect is not considered [178].

3.2.2.4 Battery System

Electricity can be stored in batteries in case of more power generation than the demand, whereas; it can be withdrawn when generation is insufficient to meet the load demand. The energy of a battery system can be estimated by appropriate assessment of the state of charge (SOC) of the battery system, which is considered as [177]

$$\frac{\mathrm{SOC(t)}}{\mathrm{SOC(t-1)}} = \int_{t-1}^{t} \frac{\mathrm{Pb(t)}\times \eta_{\mathrm{batt}}}{\mathrm{V_{bus}}}\, \mathrm{dt} \quad (3.8)$$

where, $\mathrm{Pb(t)}$ is battery output/input power, $\mathrm{V_{bus}}$ is bus voltage, η_{batt} is battery's round trip efficiency that can further be defined as

$$\eta_{batt} = \left(\sqrt{\eta_{batt\_c} \times \eta_{batt\_d}}\right) \quad (3.9)$$

where, η_{batt_c} and η_{batt_d} are battery charging and discharging efficiencies [177].

In this study, the round trip efficiency is taken 92.2%, along with charging and discharging efficiencies, 85% and 100%, respectively. The total capacity of the battery bank defines the maximum SOC (SOC_{max}) that can be computed as [177]

$$C_n(Ah) = \frac{N_{batt}}{N_{batt\_s}} \times C_b(Ah) \quad (3.10)$$

where, $C_b(Ah)$ represents the single battery capacity, N_{batt} is the total number of batteries and N_{batt_s} are total batteries connected in series to attain the desired voltage level that can be computed as

$$N_{batt\_s} = \frac{V_{bus}}{V_{batt}} \quad (3.11)$$

where, N_{batt_s} is battery count connected in series and V_{batt} is the voltage of a particular battery. One more foremost factor in the maximum power (discharge or charge) at a particular time is an important parameter in battery modelling that depends on the maximum charging current (I_{max}) computed as

$$P_{b\_max}(t) = \frac{N_{batt} \times V_{batt} \times I_{max}}{1000} \quad (3.12)$$

3.2.2.5 Converter

The proposed system consists of AC and DC components, so power converters are essential to convert power from DC to AC and vice versa. The size of the converter is considered as per the peak load ($P_{ld}(t)$) demand.

$$P_{inv}(t) = \frac{P_{ld}(t)}{\eta_{inv}} \quad (3.13)$$

where, η_{inv} is the efficiency of the inverter [177].

3.2.3 Problem formulation and operational strategy for MSW based microgrid

This study aims to propose a reliable and economically optimum hybrid system that can process the given MSW for electricity generation and can meet the mentioned load demand. The capacity of AD and gasifier systems is taken as per the amount of MSW available. The capacity of the battery bank and PV system is the significant result variables. These are determined using the operational strategy and algorithm given below.

(a) If the total power generated from biogas, gasifier, and PV is adequate to meet the load demand, then the load is served by these three systems only. After that, if the generated power of these three systems is greater than the load demand, the surplus power is used to charge the battery bank, which is represented as

$$P_{b\_ch}(t) = \left(P_{bio}(t) + P_{gasi}(t)\right) - (P_{ld}(t) \times \eta_{rec}) + \left(P_{pv}(t)\right) \quad (3.14)$$

where, $P_{ld}(t)$ is load demand and η_{rec} is the efficiency of the rectifier, P_{pv} is the total power generated by the PV system that can be computed as

$$P_{pv}(t) = P_{sol}(t) \times N_{sol} \quad (3.15)$$

where, N_{sol} is total number of PV panels.

(b) If the $P_{b\_ch}(t)$ is more than the capacity of the battery bank, the surplus power will be sent to the utility grid that can be calculated as

$$P_{Gs}(t) = P_{b\_ch}(t) - \left(P_{bmax}(t) - P_{b(t-1)}\right) \quad (3.16)$$

where, $P_{Gs}(t)$ is power sold to grid and in the islanded mode this energy will be the dump energy.

(c) If the power output of biogas, gasifier, and PV system is insufficient to supply the load demand, the balance power will be supplied by the battery bank.

$$P_{b\_dch}(t) = \frac{\left(P_{ld}(t) - \left(\left(P_{pv}(t) \times \eta_{inv}\right) + P_{bio}(t) + P_{gasi}(t)\right)\right)}{\eta_{inv}} \quad (3.17)$$

(d) If at any time the SOC of battery is not sufficient to supply the deficient amount of power means if,

$$P_{b\_dch} > \left(\mathrm{P_b}(\mathrm{t}-1) - \mathrm{P_{b\_min}}(\mathrm{t})\right) \quad (3.18)$$

Then rest power will be taken from the grid as follows

$$P_{Gp}(t) = \mathrm{P_{b\_dch}}(\mathrm{t}) - \left(\mathrm{P_b}(\mathrm{t}-1) - \mathrm{P_{b\_min}}(\mathrm{t})\right) \quad (3.19)$$

where, $P_{Gp}(t)$ is power purchased from grid and $\mathrm{P_{b\_min}}(\mathrm{t})$ is the minimum power capacity of battery bank that depends upon the minimum SOC selected. In the present case, the PV and battery system capacities are estimated by keeping the microgrid in islanded mode. In islanded mode $P_{Gp}(t)$ will not exist, and a penalty function is used after equation (3.18) to satisfy the load demand with biogas, gasifier, PV, and battery bank. The operating strategy is discussed above in the simplified flow chart Figure 3.4.

3.2.3.1 Objective function and constraints

The objective of optimizing the proposed hybrid system is to reduce the total net present cost of the system while maintaining a reliable energy flow. There are two decision variables i.e. N_{sol} (number of PV panels) and N_{batt} (number of batteries) that will decide the optimal arrangement of the proposed system. For the financial evaluation, the ASC method is adopted. The lowest ASC result is taken as the best one while satisfying the selected constraints.

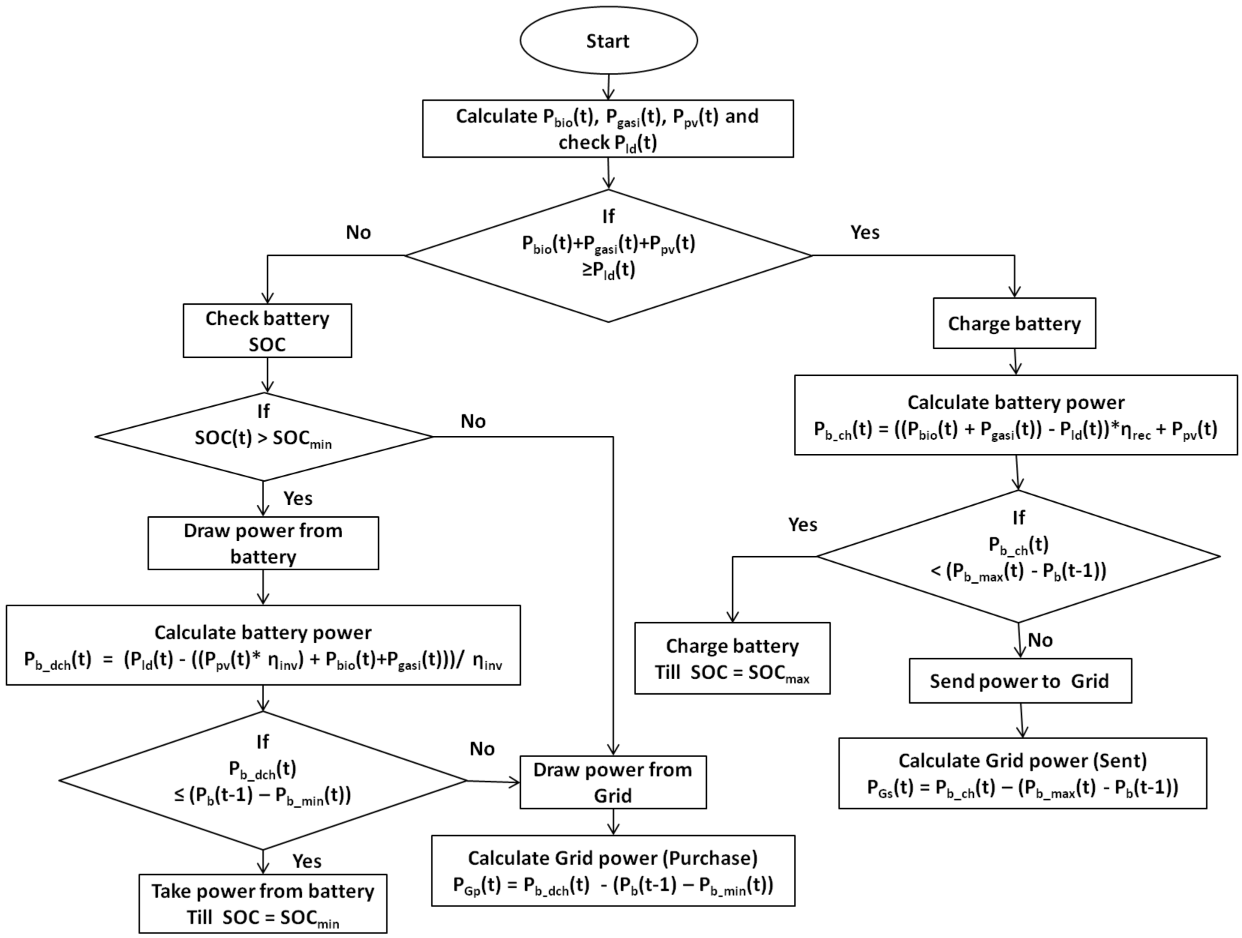

Figure 3.4: Flow chart of operating strategy for the present system

The overall system cost is taken as the objective function that consists of capital cost, operating and maintenance cost, and replacement cost of all the components used in the proposed hybrid system. The function given below is taken as the key function to be minimized subject to selected constraints.

$$Minimise\ ASC = F\left((P_{bio} \times C_{bio}) + (P_{gasi} \times C_{gasi}) + (N_{sol} \times C_{sol}) + (N_{batt} \times C_{batt}) + (P_{con} \times C_{con})\right) \quad (3.20)$$

where, C_{bio}, C_{gasi}, C_{sol}, C_{batt} and C_{con} are the costs of the biogas system (per kW), gasifier (per kW), solar (per kW), battery (per unit), and converter (per kW), respectively.

The ASC of the entire components has several parts like capital cost(C_{cap}), operating and maintenance cost per year(C_{op}), replacement cost(C_{rp}), salvage cost(C_{sl}).

The total ASC of every element can be expressed as

$$C_{bio} = C_{bio\_cap} + C_{bio\_op} + C_{bio\_rp} - C_{bio\_sl} \quad (3.21)$$

$$C_{gasi} = C_{gasi\_cap} + C_{gasi\_op} + C_{gasi\_rp} - C_{gasi\_sl} \quad (3.22)$$

$$C_{sol} = C_{sol\_cap} + C_{sol\_op} + C_{sol\_rp} - C_{sol\_sl} \quad (3.23)$$

$$C_{batt} = C_{batt\_cap} + C_{batt\_op} + C_{batt\_rp} - C_{batt\_sl} \quad (3.24)$$

$$C_{con} = C_{con\_cap} + C_{con\_op} + C_{con\_rp} - C_{con\_sl} \quad (3.25)$$

The annualized cost of all the elements is calculated using the capacity recovery factor (CRF) as mentioned below

$$\mathrm{CRF(i, N)} = \frac{i(1+i)^N}{i(1+i)^N - 1} \quad (3.26)$$

Where, i is the annual interest rate, and N is the lifetime of the project in years.

Enforcing the number of constraints listed below, the objective function is minimized

$$1 \leq \mathrm{N_{sol}} \geq \mathrm{N_{sol\_max}} \quad (3.27)$$

$$1 \leq \mathrm{N_{batt}} \geq \mathrm{N_{batt\_max}} \quad (3.28)$$

$$SOC_{min} < SOC > SOC_{max} \quad (3.29)$$

Where, $\mathrm{N_{sol\_max}}$ is the maximum number of PV panels and $\mathrm{N_{batt\_max}}$ is the maximum number of batteries. Based on reliability and LCOE, the optimal arrangement of the system is selected. LCOE is calculated as the average price of useful power/kWh obtained from the hybrid system as mentioned below

$$\mathrm{LCOE} = \frac{ASC\left(\frac{INR}{Year}\right)}{\text{Total load demand served+Power sold to grid}} \quad (3.30)$$

3.2.4 Artificial bee colony optimization

Karaboga and Basturk proposed ABC optimization algorithm in 2005. It is basically swarm-based algorithm that is motivated by the intellectual behavior of honey bees.

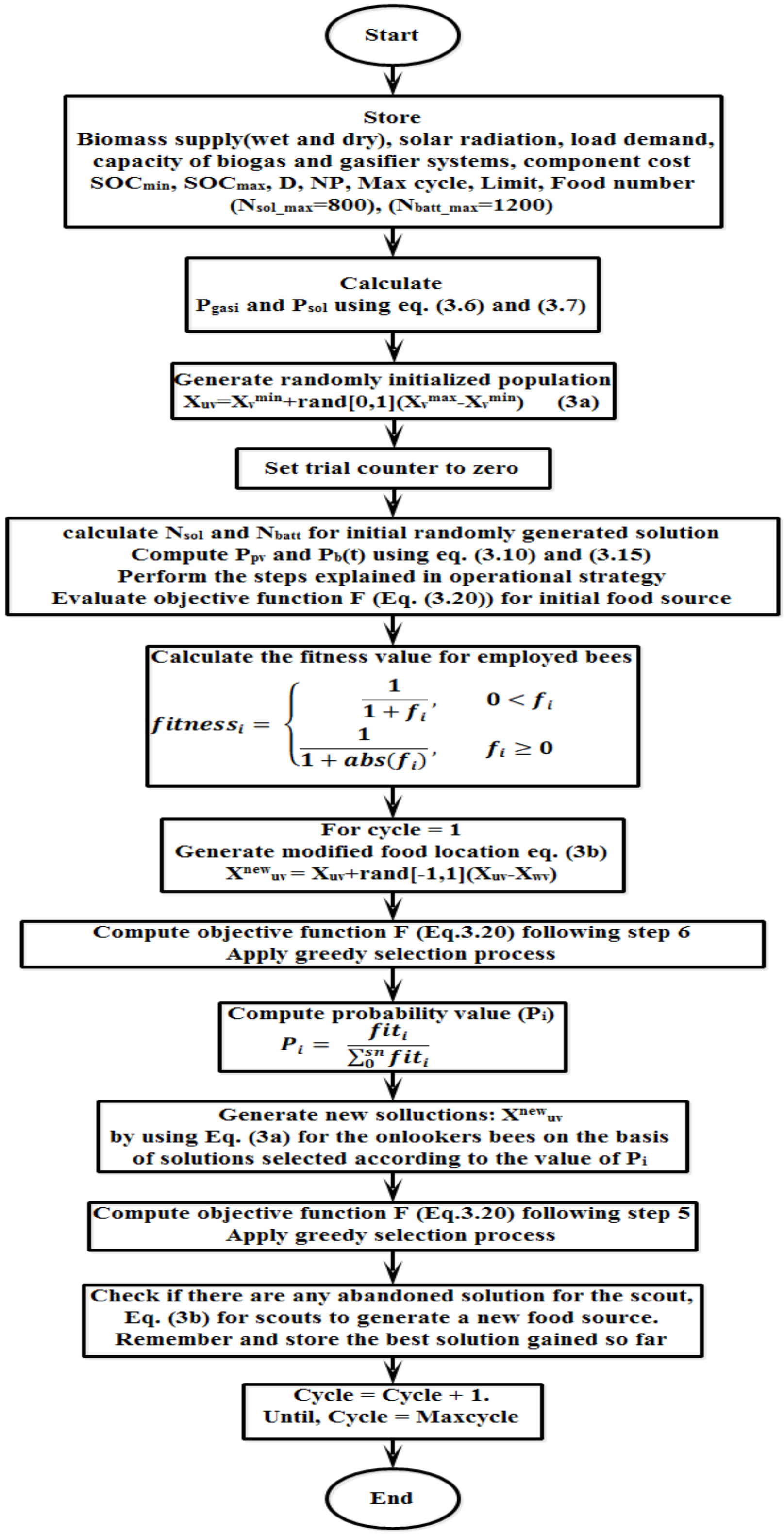

Figure 3.5: ABC algorithm execution

A honey bee colony is an extremely structured social organization with three types of bee groups i.e. employed, onlooker and scout. A specific food source is exploited by each bee by random selection and the information about that source is shared with onlooker bees. The onlooker bees then decide to explore the food source based on the information. If the information received from employed bees does not improve the source, then the food source is abandoned, and the employed bees turn into scouts [179]. The algorithm, along with the proposed methodology given in flow chart Figure 3.5, is used to solve the present problem.

3.2.5 Results and discussion on MSW based microgrid

The proposed methodology is simulated in Matlab software, and results are obtained using ABC algorithm. The technical and economic parameters of all the equipment considered for this study are presented in Table 3.2. The experiment is done on a data set of input values of one year taking a simulation time step of one hour. Table 3.3 shows the control parameters of the selected algorithm. The capacity of biogas and gasifier is taken 32 and 64 kWh, whereas the maximum number of PV panels (N_{sol_max}) and batteries (N_{batt_max}) are considered 800 and 1200. The rating of the converter is not taken as a decision variable. It is kept at 215 kW as per peak load demand. The total cost of the hybrid system consists of the cost of biogas, gasifier, PV, battery bank, and convertor.

The optimum result depends upon the number of PV panels and batteries because all other parameters are fixed. On the basis of ASC and LCOE, the most optimum result is selected. The optimized result obtained by the ABC algorithm is presented in Table 3.4. The conversion rate of the ABC algorithm is shown in Figure 3.6. It can be noted that the algorithm converges in about 30 iterations. The predicted number of PV panels and batteries, along with ASC and LCOE is shown in Table 3.4. The complete detail of the ASC of the proposed hybrid system is given in Table 3.5. The annualized cost of all the components is calculated using CRF. No replacement is required for biogas, gasifier, PV and converter because all these have the same life that the project is 20 years. The life of batteries is five years, so for a project life span of 20 years, these need to be replaced three times. Out of the total cost of the hybrid system, biogas and gasifier contribute 15 and 33%, whereas solar and battery contribute 34 and 13%. The energy production by all the sources is given in Table 3.6. It can be noted that the solar system generates the highest power, followed by the gasifier and biogas system.

Table 3.2: Economic and technical parameters of selected components

Component	Parameter	Value	Unit
Biogas system	Rated power	1	kW
	Capital cost	134166	INR/kW
	O & M cost	9066	INR/kW/yr
	Replacement cost	134166	INR/kW
	Lifetime	20	Year
Gasifier system	Rated power	1	kW
	Capital cost	155700	INR/kW
	O & M cost	9016.74	INR/kW/yr
	Replacement cost	155700	INR/kW
	Lifetime	20	Year
PV	Rated power	1	kW
	Capital cost	84000	INR/kW
	O & M cost	280	INR/kW/yr
	Replacement cost	84000	INR/kW
	Lifetime	20	Year
Battery	Capital cost	11690	INR/unit
	O & M cost	116.9	INR/unit
	Replacement cost	4690	INR/unit
	Lifetime	5	Year
	Nominal voltage	6	V
	Nominal current	360	Ah
	Maximum SOC	100	%
	Minimum SOC	30	%
Converter	Rated power	115	kW
	Capital cost	8890	INR/kW
	O & M cost	70	INR/kW/yr
	Replacement cost	8890	INR/kW
	Lifetime	20	Year
	Efficiency (inverter and rectifier)	90	%
	Project life	20	Year
Others	Interest rate	6	%
	Bus voltage	120	V
	Batteries in string	20	Units

Table 3.3: Parameters of selected algorithm

ABC	
Number of bees (employed and onlooker)	10
Problem dimension (D)	2
Size of colony (NP)	20
Food number	10
Maximum number of cycles	190
Limit	20

Table 3.4: Results of selected algorithm for optimal sizing of the hybrid system

Algorithm	Biogas system (kW)	Gasifier system (kW)	PV (units)	Battery (units)	Inverter (kW)	ASC (INR/year)	NPC (INR)	LCOE (INR/kWh)
ABC	32	64	260.5	532	215	5.77E+6	6.61E+7	5.65

Table 3.5: Complete detail of ASC for the proposed hybrid system

Component	Capital cost (INR/yr)	Maintenance cost (INR/yr)	Replacement cost (INR/yr)	Fuel Cost (INR/yr)	Salvage value (INR/yr)	Total cost (INR/yr)
Biogas	3.75E+5	4.36E+5	------	1.06E+5	------	8.10E+5
Gasifier	8.69E+5	9.52E+5	------	9.53E+4	------	1.82E+6
PV	1.91E+6	7.30E+4	------	------	------	1.99E+6
Battery	5.43E+5	6.22E+4	1.63E+5	------	------	7.68E+5
Inverter	1.67E+5	1.51E+4	------	------	------	1.82E+5

The total load demand of one year is satisfied with the proposed hybrid system that consists of biogas, gasifier, PV and battery bank. The monthly energy balance of the complete year for the hybrid system is given in Figure 3.7. After meeting the load demand, the system has 1.63×10^5 kWh of surplus energy, which is 18.9 % of the load demand, and it can be sent to the grid. The operation of the hybrid system is verified for a complete year by selecting a time period of two weeks. The first week of January and July are considered because January has minimum load demand and July has the highest load demand. The energy balance for the first week of January is shown in Figure 3.8. In this month, as per the supply of biomass, the biogas and gasifier run at 62% and 75% of their rated capacity and generate 3366 and 8105 kWh of total power in the first week of January. The solar system is giving output for nine hours in a day and generates 6006 kWh of total power this week. The total power supplied by the battery is 2339 kWh, and the power sent to the grid is 3272 kWh after meeting the total load demand of 1.29×10^4 kWh for this week. The minimum SOC of the battery is 72%.

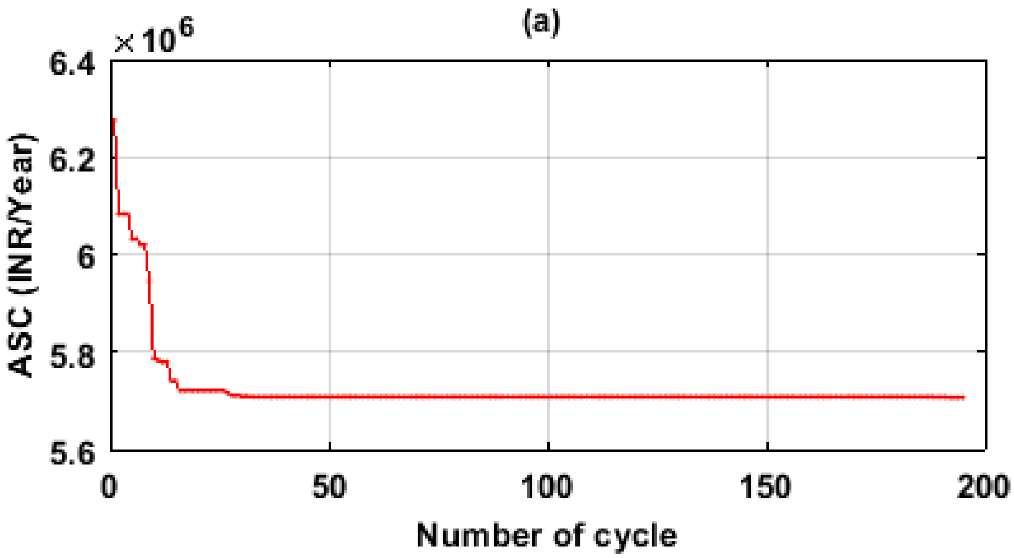

Figure 3.6: Convergence rate ABC algorithm

Table 3.6: Energy analysis of proposed system

Component	kWh/year
Biogas	2.11E+5
Gasifier	4.15E+5
PV	4.83E+5
Battery in	2.37E+5
Battery out	2.18E+5
Load served	8.58E+5
Power to grid	1.63E+5

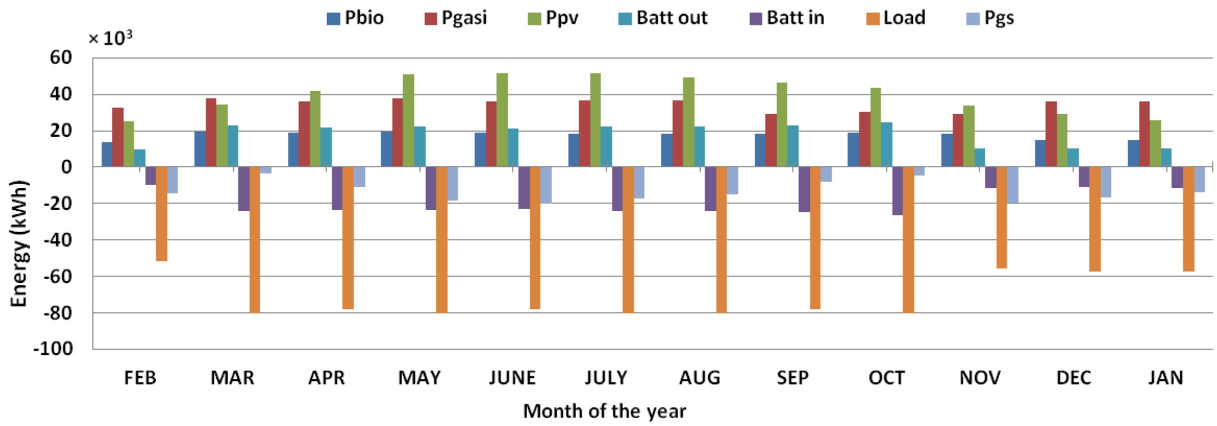

Figure 3.7: Month-wise analysis of power generation by different sources

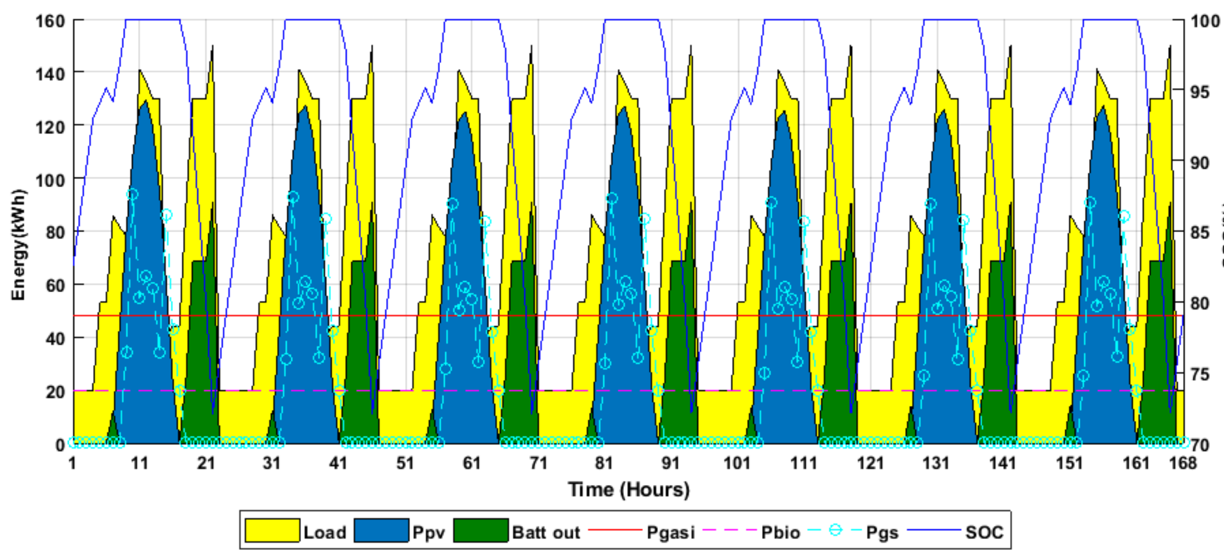

Figure 3.8: Energy balance for the first week of January

In the first week of July, the biogas and gasifier system runs at 76% of their rated capacity and generates 4114 and 8212 kWh of total power, as shown in Figure 3.9. These parameters are higher as compared to the first month of January because of the change in the supply of feedstock which increases in July. The solar system is giving output for 12 hours in a day and generates 1.19×10^4 kWh of total power in this week. The total power supplied by the battery is 5.03×10^3 kWh, and power sent to the grid is 4071 kWh after meeting the total load demand of 18148 kWh for this week. The minimum SOC of the battery is 36%. In the summer season, the biogas, gasifier, and solar systems generate more power than in the winter season. At the same time, the load demand is also more in summer as compared to winter; that's why the SOC of the battery goes a minimum of 36% because the battery has to supply more power in summer. The power sent to the grid is also higher by a small value in summer.

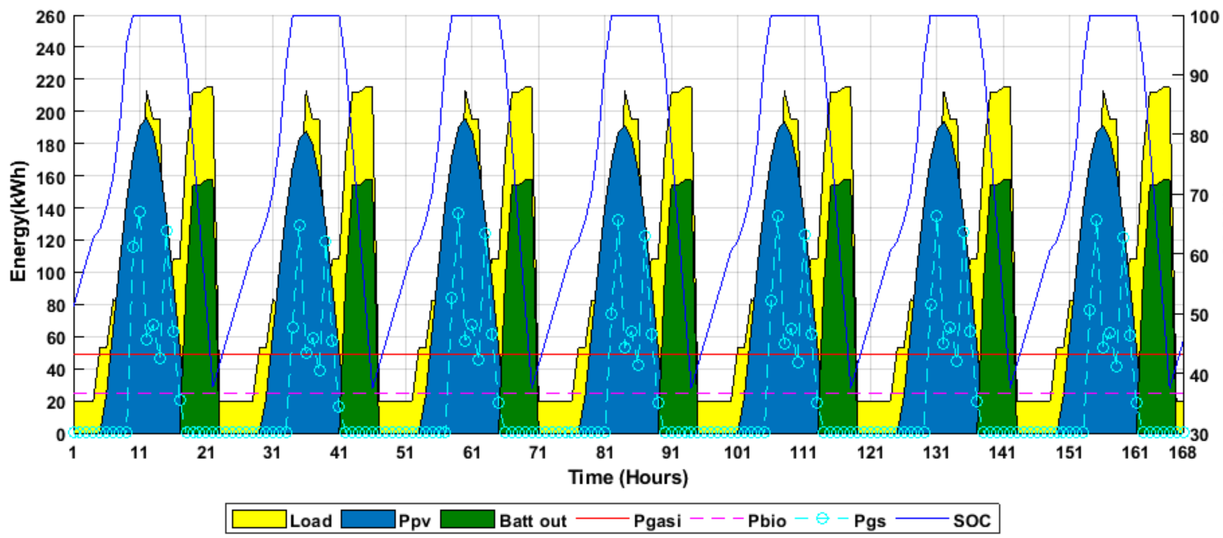

Figure 3.9: Energy balance for the first week of July

The measurement of the SOC of the battery is an essential issue for a hybrid system consisting of a battery bank. The SOC of the battery for the proposed system is shown in Figure 3.10, along with the input and output energy of the battery for one year.

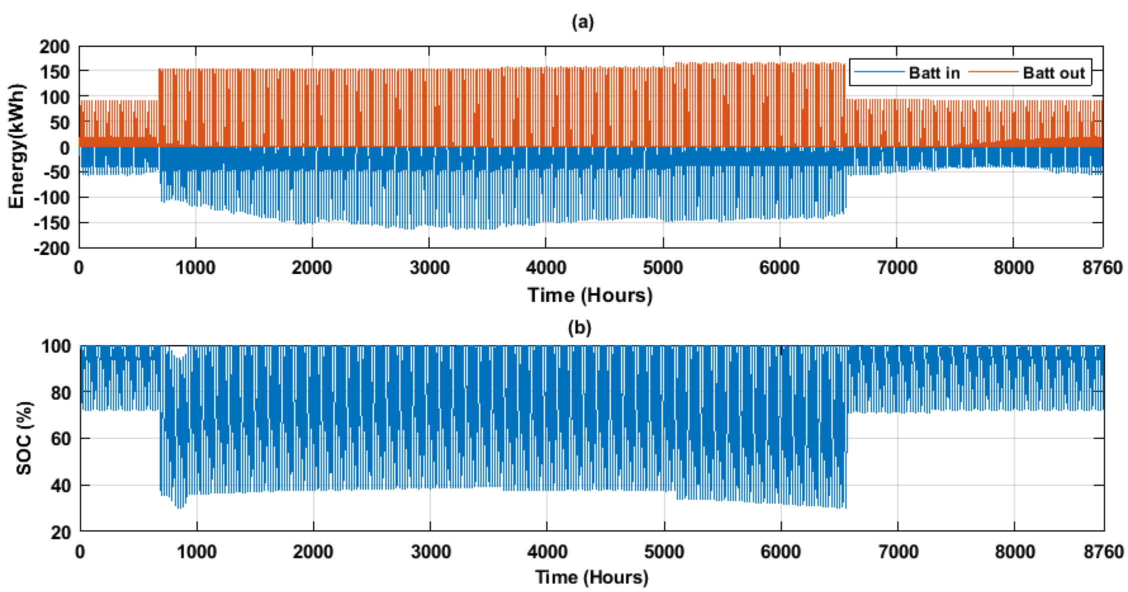

Figure 3.10: (a) Battery charging and discharging power (b) Battery SOC of a complete year

The starting and minimum SOC of the battery system is considered as 100% (1140 kWh) and 30% (342 kWh). It can be noted that in winter, SOC remains 72% to 100%, and in summer, most of the time it remains 36% to 100%. SOC goes at a minimum level of 30% in summer only for a few hours, in the starting of March and the end of November due to less power coming from the PV system because of low radiation. Another important factor in the case of the battery is charging and discharging current monitoring. For efficient performance, the maximum charging/discharging power is calculated using equation (3.12) and found to be 165 kWh at 0.14 C-rate. If the availability of power exceeds the charging limit, then it will be sent to the grid. If discharging power is greater than the discharging rate, then the power will be taken from the grid.

The battery's round trip efficiency is another important parameter, and it is necessary to estimate its effect on LCOE. Previously, round trip efficiency is considered 92.2%. To make the study more sensible, the LCOE for different round trip efficiencies is calculated and presented in Figure 3.11(a). It can be noted that the LCOE decreases significantly with an increase in the battery's round trip efficiency. Moreover, the economic performance of the microgrid system is sensitive to market factors such as interest rates. The capital cost of major components is directly linked to the interest rate. In view of this, the impact of interest rate on LCOE is investigated, as shown in Figure 3.11(b). This indicates that the LCOE increases in proportional to the interest rate. Further, the effect on LCOE of disturbance in feedstock supply chain or decrease in efficiency of AD and gasifier system is estimated and presented in Figure 3.12. For this, a decrease of 10% of total power production by AD and gasifier is considered. The LCOE increases in proportional to the decrease in power production.

The total cost of MSW processing comes to be INR 2.63×10^6 (3.43×10^4 USD), including the cost of AD INR 8.09×10^5 (1.05×10^4 USD) and gasifier INR 1.82×10^6 (2.37×10^4 USD) in one year. A total of 3658.18 tonnes of MSW is processed that including 1907.42 tonnes by AD and 1745.76 tonnes by gasifier. The cost for landfilling of MSW in India is INR 123.7 (USD1.61)/tonne per day [175]. The net amount of 4.52×10^5 (5.89×10^3 USD) INR is saved by avoiding the landfilling of waste that is processed by AD (INR 2.35×10^5 /USD 3079) and gasifier (INR 2.16×10^5 /USD 2818). The month-wise MSW processing and saved costs are presented in Figure 3.13.

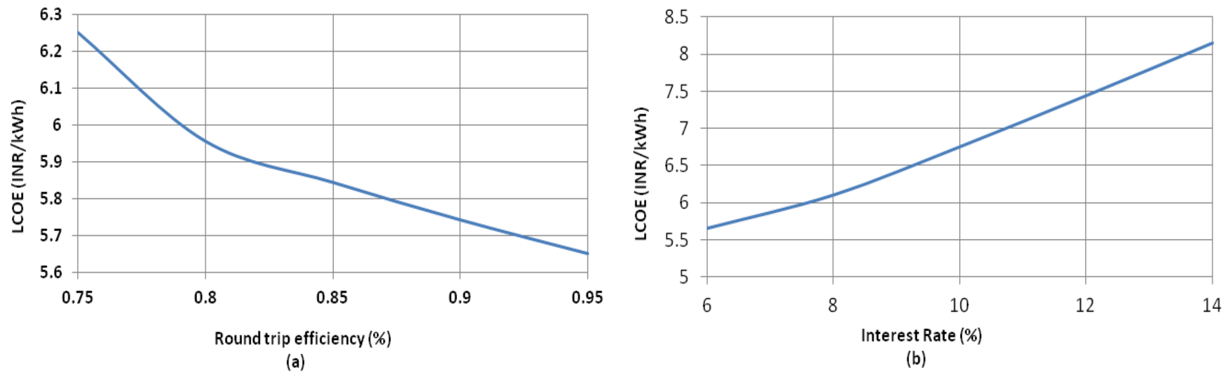

Figure 3.11: (a) Change in LCOE with respect to Battery's round trip efficiency (b) Change in LCOE with respect to interest rate

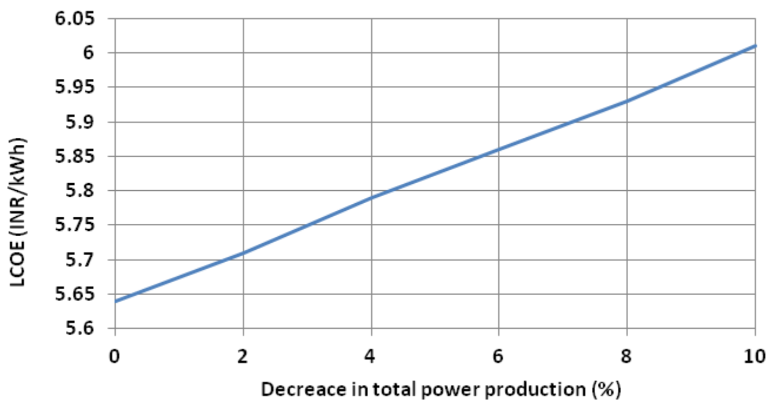

Figure 3.12: Change in LCOE with respect decrease in power production of AD and gasifier

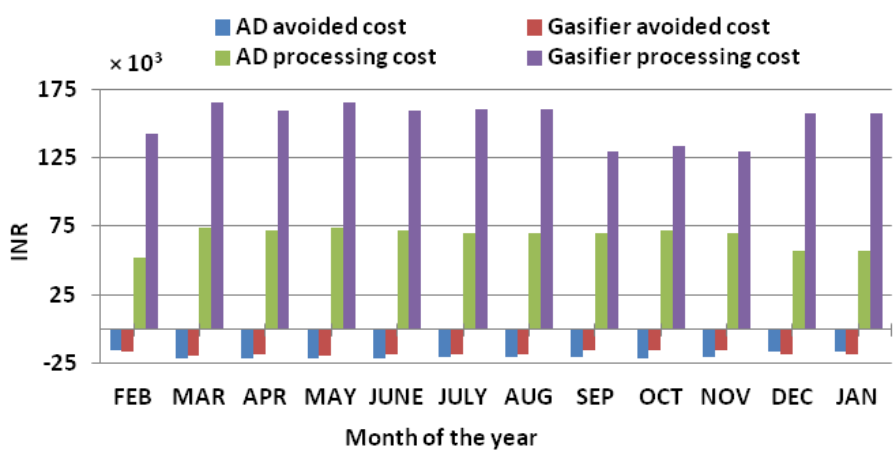

Figure 3.13: Month-wise MSW processing and avoided cost by selected technologies

The net saved cost of MSW is 17% of its total processing cost for the whole year. Table 3.7 shows the global weighted average LCOE of various technologies for 2019 [180]. The hydro system is reported as the cheapest power generation system, with a global weighted average LCOE of 0.047 USD/kWh. The weighted average LCOE of the bioenergy system is reported at 0.066 USD/kWh. But for Europe and North America, the bioenergy systems are reported LCOE of 0.08 USD/kWh and USD/kWh 0.099, respectively. The LCOE of the proposed system is found to be competitive with the present scenario.

3.2.5.1 Validation of results of MSW based microgrid

The obtained results are validated by the PSO algorithm. The experiment is done on the same dataset data set of input values of one year, considering the same simulation time step of one hour.

Table 3.7: Global weighted average LCOE of various electricity generation technologies [180]

Technology	PV	PV roof top	Concentrating Solar Power	Geothermal	Bioenergy	Wind onshore	Wind offshore	Hydro	Coal
LCOE USD/kWh	0.068	0.062	0.08	0.073	0.066	0.053	0.115	0.047	0.05

The control parameters of the PSO algorithm are shown in Table 3.8. The predicted number of PV panels and batteries, along with ASC and LCOE, is shown in Table 3.9. Results show that the PSO algorithm gives the same result for the present problem. So to investigate the reliability and economic factors of the proposed system, the results of the ABC algorithm can be trusted.

Table 3.8: Parameters of selected algorithm

PSO	
Population size (N)	20
Problem dimension (D)	2
Initial weight (W_{min})	0.4
Final weight (W_{max})	0.9
Maximum number of iterations	190
Weighting factors (C_1 and C_2)	2

Table 3.9: Results of PSO algorithm for optimal sizing of the hybrid system

Algorithm	Biogas system (kW)	Gasifier system (kW)	PV (units)	Battery (units)	Inverter (kW)	ASC (INR/year)	NPC (INR)	LCOE (INR/kWh)
PSO	32	64	260.7	532.5	215	5.77E+6	6.61E+7	5.65

3.2.6 Environmental evaluation of MSW based microgrid

In this section, the proposed microgrid is evaluated for its environmental impacts using the LCA methodology. The adopted methodology (LCA) is discussed prior in chapter 2. The input data related to transportation of MSW, AD, gasification and landfilling, and coal-based electricity emissions is also given in chapter 2.

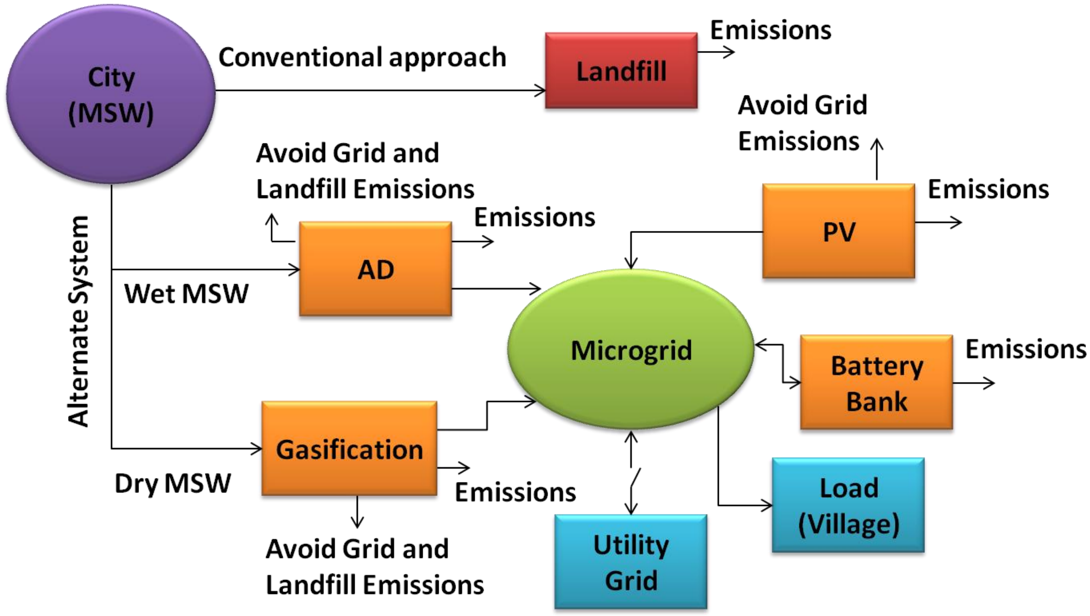

Figure 3.14: System boundaries for the environmental assessment study

Figure 3.14 shows the hybrid electricity generation system boundary. The ecological limit is restricted to the Indian state of Punjab. The processing of MSW consists of two phases wet and dry. The system boundary starts with the transportation of MSW and then its processing to produce electricity. The AD processes wet MSW and produce biogas further converted to electricity; similarly, gasification processes dry MSW and produces electricity as a final product. System boundary includes the emission of MSW processing by both the techniques to the final product produced at each stage. For the PV and battery system, only CO_2 emissions during the manufacturing of PV panels and batteries are considered. The electricity produced from the hybrid system is assumed to replace coal-based electricity. The emissions from the collection of MSW are not considered because the collection of MSW is necessary for society even if the waste is not going to process and will be dumped. System boundary also consists of landfill avoided emissions that are the landfill emissions for an amount of MSW which is processed to produce the desired product. This study does not consider the emissions related to infrastructure and land used for the system.

Considering the LCA methodology (discussed in chapter 2), the environmental impact of the proposed system is evaluated. That is discussed below for the global warming potential (GWP), acidification potential (AP), photochemical oxidants creation potential (POCP), and eutrophication potential (EP) categories.

3.2.6.1 Global warming potential

The proposed hybrid system shows a net reduction of -4.98×10^6 kg CO_2 eq./year for this category. In the net reduction, AD contributes -2.65×10^6, gasification $-1.45\times10^{6,}$ and PV -8.76×10^5 kg CO_2 eq./year, as shown in Figure 3.15. Here, AD shows the highest reduction potential because of higher landfill avoiding emissions and low processing emissions compared to gasification, as given in Table 3.10. Gasification has higher converting CO_2 emissions than AD, which primarily adds to this class. Due to more MSW processing, AD has more landfill avoiding emissions than gasification. However, due to more efficiency, gasification has higher electricity avoiding emissions than AD. The PV system has minimal processing emissions and the highest electricity avoided emissions compared to all other technologies. The total emissions occurred from the battery system are 5.93×10^4 kg CO_2 eq./year. It can be noted that MSW processing techniques have smaller installed capacities than PV and higher processing emissions but have a very high carbon emission reduction tendency than PV. Both the MSW processing techniques have a great benefit of landfill-avoiding factors. The landfill of MSW has high CO_2 and CH_4 emissions, which are the primary cause of global warming.

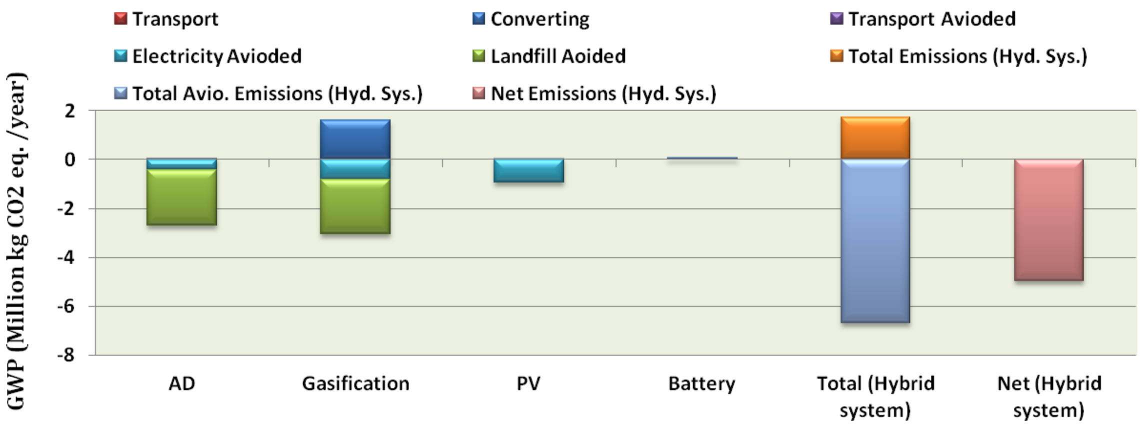

Figure 3.15: GWP impact of proposed microgrid

Table 3.10: Emissions from microgrid for GWP category (kg/year)

			CO_2	CH_4	CO	Total CO_2 eq.
AD	Process Emissions	Converting	2.96E+4	3.58E+2	2.71E+2	3.90E+4
		Transport	7.55E+2	13.2E-2	5.3	7.69E+2
	Avoided Emissions	Landfill	-2.25E+5	-8.19E+4	-13.8	-2.28E+6
		Electricity	-2.56E+5	-6.33E+3	-1.89E+3	-4.18E+5
		Transport	-7.55E+2	-13.2E-2	-5.3	-7.69E+2
	Net					-2.65E+6
Gasification	Process Emissions	Converting	1.62E+6	0	1.75E+2	1.62E+6
		Transport	745	0.13	5.23	758
	Avoided Emissions	Landfill	-2.22E+5	-8.08E+4	-13.61	-2.24E+6
		Electricity	-5.02E+5	-1.25E+4	-3.72E+2	-8.19E+5
		Transport	-745	-0.13	-5.23	-758
	Net					-1.45E+6
PV	Process Emissions	Manufacturing	1.94E+4			1.94E+4
	Avoided Emissions	Electricity	-9.56E+5			-9.56E+5
	Net					-9.36E+5
Battery	Process Emissions	Manufacturing	5.93E+4			5.99E+4
	Net					5.93E+4
Net of Microgrid						-4.98E+6

3.2.6.2 Acidification potential

For the acidification potential category, the hybrid system shows a net reduction of -11781 kg SO_2 eq./year, as shown in Figure 3.16. Here gasification contributes- 3955, AD contributes -2515 and PV contributes -5311kg SO_2 eq./year in total reduction. Here PV system shows the highest reduction in emissions in comparison to all other technologies, which are due to higher electricity avoided emissions and the absence of conversion emissions, as presented in Table 3.11. The coal-based power generation has SO_2 and NO_X emissions that are well-known constituents of this category. The conversion emissions of gasification are almost double that of AD. The processing of MSW by gasification emits more SO_2 and NO_X than its processing by AD. AD has larger landfill avoided emissions than gasifier that is due to processing more amount of waste. On the other hand, due to more electricity generation potential, gasification has more electricity avoided emissions than AD, making it better than AD for this category.

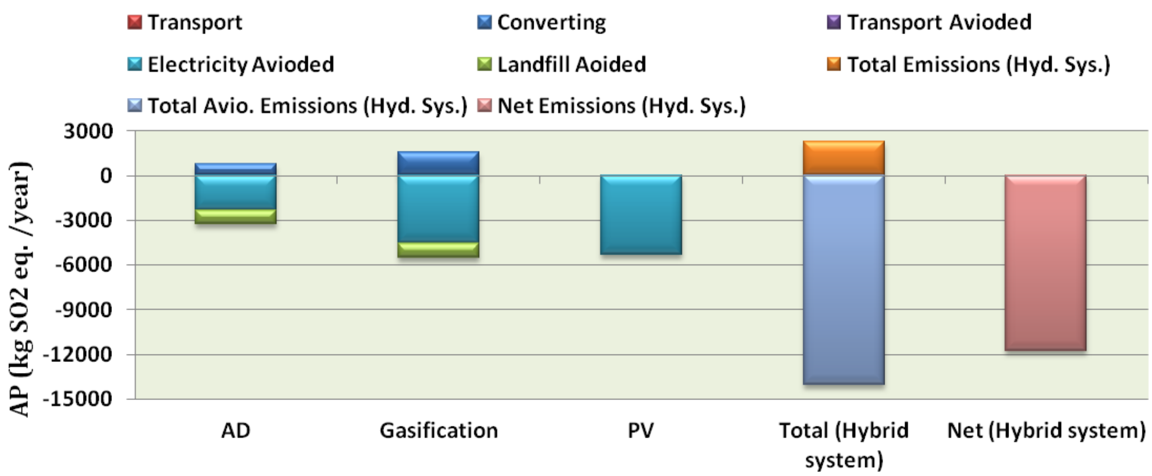

Figure 3.16: AP impact of proposed microgrid

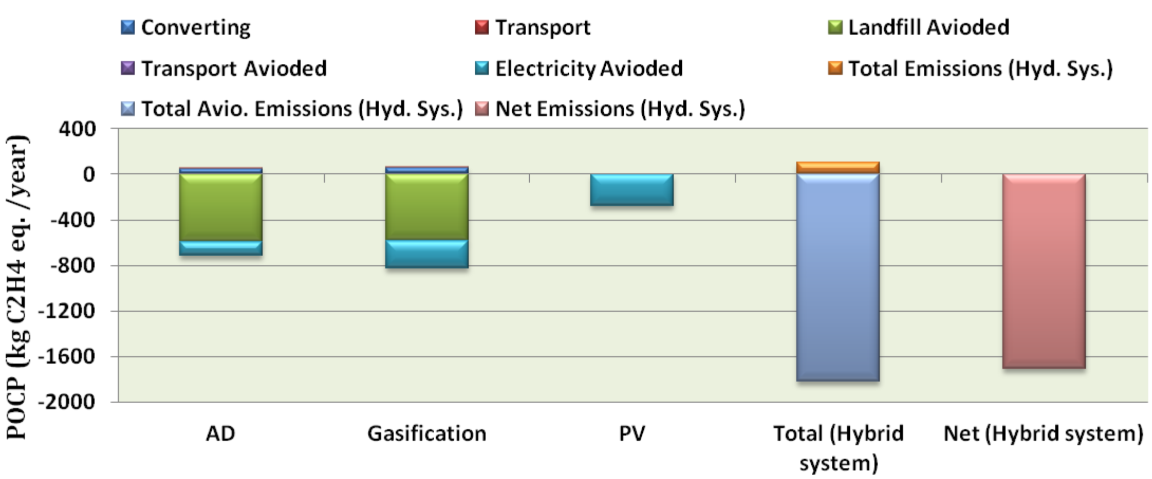

Figure 3.17: POCP impact of proposed microgrid

3.2.6.3 Photochemical oxidation potential

The hybrid system shows a net reduction of -1713 kg C_2H_4 eq./year for this category, as shown in Figure 3.17. In this total reduction AD contributes -670, gasification -767 and PV contributes -276 kg C_2H_4 eq./year. Both the MSW processing technologies perform better than PV due to landfill avoiding emissions, as shown in Table 3.12. PV system has the highest electricity avoided emissions and zero conversion emissions, but due to the replacement of CH_4, CO, NO_X, and VOC from landfill emissions, AD and gasifiers perform better. In comparison to AD, gasifier has reduced more emissions in this category. The difference is due to more electricity generated by gasification, resulting in more electricity avoiding emissions.

Table 3.11: Emissions from microgrid for AP category (kg/year)

			SO_2	NO_X	H_2S	HCl	HF	Total SO_2 eq.
AD	Process Emissions	Converting	3.34	1064	2.79			753
		Transport	2.09	9.29				8.60
	Avoided Emissions	Landfill	-9383	-1203		-5.31	-5.31	-949.7
		Electricity	-1581	-1054				-2319
		Transport	-2.09	-9.29				-8.60
	Net							-2515
Gasification	Process Emissions	Converting	90.77	1361		558	0.59	1536
		Transport	2.06	9.16				8.48
	Avoided Emissions	Landfill	-92.52	-1187		-5.23	-5.23	-936.49
		Electricity	-3105	-1449				-4555
		Transport	-2.06	-9.16				-8.48
	Net							-3955
PV								
	Avoided Emissions	Electricity	-3621	-2414				-5311
	Net							-5311
Net of Microgrid								-11781

3.2.6.4 Eutrophication potential

This category proposed system shows a net reduction of -818 kg PO_4 eq./year, as shown in Figure 3.18. In this total reduction, AD contributes -206, gasification -297, and PV -313 kg PO_4 eq./year. AD has more landfill avoided emissions and fewer conversion emissions than gasification. Though, due to higher power generation potential than AD, gasification reduced more overall emissions for this category, as depicted in Table 3.13. The coal-based power and landfilling of MSW have NO_X emissions that mainly contribute to this category. Similarly, the PV system has produced a much more significant amount of electricity than AD, and gasifiers also don't have conversion emissions. That's why PV leads all other technologies due to more electricity avoided emissions.

Table 3.12: Emissions from microgrid for the POCP category (kg/year)

			CH_4	CO	NO_X	VOC	Total C_2H_4 eq.
AD	Process Emissions	Converting	358	271	1064	7.80	46
		Transport	0.13	5.31	9.29		0.42
	Avoided Emissions	Landfill	-1.89E+4	-13	-1203	-113	-595
		Electricity	-6326	-1897	-1054		-120
		Transport	-0.13	-5.31	-9.29		-0.42
	Net						-670
Gasification	Process Emissions	Converting		174	1361	19	57
		Transport	0.13	5.23	9		0.41
	Avoided Emissions	Landfill	-8.08E+4	-13	-1187	-111	-587
		Electricity	-1.25E+4	-3727	-2070		-273
		Transport	-0.13	-5.23	-9		-0.41
	Net						-767
PV	Avoided Emissions	Electricity	-1.45E+4	-4345	-2414		-276
	Net						
Net of Microgrid							-1713

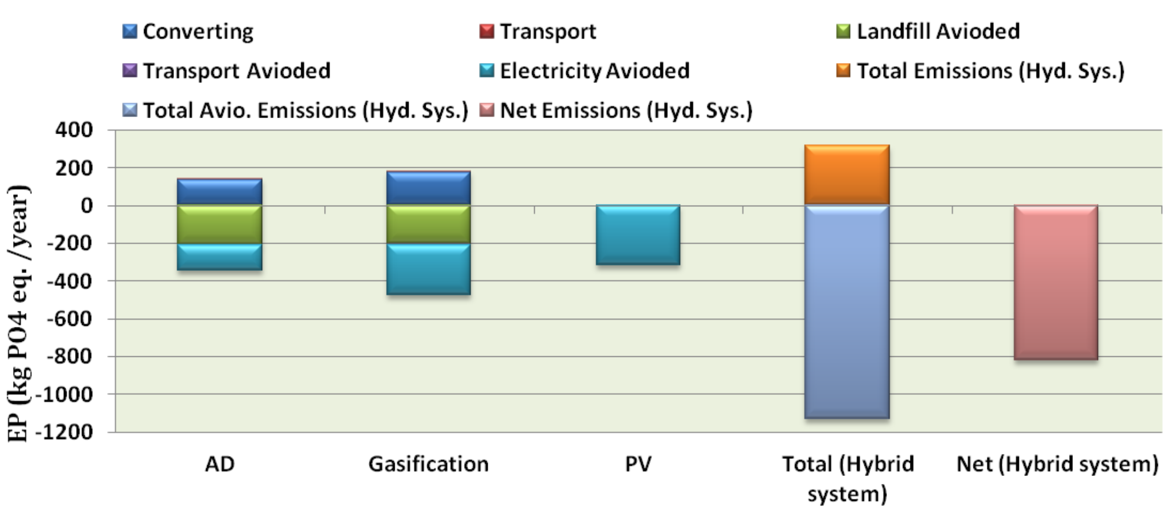

Figure 3.18: EP impact of proposed microgrid

Table 3.13: Emissions from microgrid for the EP category (kg/year)

			NO_X	Total N	BOD	COD	P	Total PO_4 eq.
AD	Process Emissions	Converting	1064	0.27E-6	0.27E-5	0.69E-6		138
		Transport	9.29					1.20
	Avoided Emissions	Landfill	-1203	-16.64	-1.72	-3.02	-0.13	-208
		Electricity	-1054					-137
		Transport	-9.29					-1.20
	Net							-206
Gasification	Process Emissions	Converting	1361					177
		Transport	9.16					1.19
	Avoided Emissions	Landfill	-1187	-1641	-1.70	-2.98	-0.13	-205
		Electricity	-2070					-269
		Transport	-9.16					-1.19
	Net							-297
PV	Avoided Emissions	Electricity	-2414					-313
	Net							-313
Net of Microgrid								-818

3.2.7 Discussions on environmental impact of MSW based microgrid

The proposed microgrid is analyzed methodically for its environmental impacts. All the technologies selected to design this microgrid are evaluated individually at each phase of the complete process. Results show that the proposed system has an immense tendency to reduce the pollution of GWP, AP, POCP, and EP environmental categories. With an installed capacity of 32 kW, 64kW of AD, and gasification technology, the system processes MSW for electricity generation. The integrated PV and battery systems have a capacity of 260.5 kW and 1149 kWh. The proposed microgrid generates 1.01×10^6 kWh/year of electricity with environmental emissions of -4.87 kg CO_2 eq./kWh, -0.01155 kg SO_2 eq./kWh, -0.00141 C_2H_4 eq./kWh, and -0.0008 kg PO_4/kWh. From the comprehensive analysis, it can be noted that the MSW processing technologies have minimal installed capacities compared to PV. But their environmental impact reduction tendency for GWP and POCP is much higher than PV. Even both the AD and gasifier technologies have processing emissions where PV doesn't. This shows the importance of waste to energy generation technologies. Landfilling of MSW has high CO_2 and CH_4 emissions that mainly contribute to GWP. AD and gasification technology avoid these emissions, making them superior for GWP reduction. Similarly, replacing CH_4, CO, $NO_{X,}$ and VOC landfill emissions that contribute to the POCP impact category makes superior AD and gasification for this category. For AP and EP impact categories, PV reduces more emission impact due to the replacement of SO_2 and NO_X grid emissions that contribute to these categories. But with minimal installed capacities compared to PV, AD and gasifier systems have impact reduction tendency in competition with PV for these categories. That is due to the replacement of SO_2 and NO_X emissions from landfills. Along with the coal-based grid emission, processing waste for electricity generation replaces the landfill emissions that have a high tendency to pollute the environment for all selected environmental impact categories. The integration of MSW processing technologies with other renewable energy generation technologies increases the environmental sustainability of the hybrid system. The proposed MSW-based microgrid can be a solution to present waste handling problems. Along with the waste management system, this microgrid could help enhance the power system's growth in an environmentally sustainable way.

3.3 Conceptualization and evaluation of rice straw based microgrid

In this section, the study proposes a rice straw-based microgrid for a small village named Mallehwal in Punjab (India). The selected village has approximately 2000 of persons that has 1000 acres of agricultural land. The microgrid is designed to process the surplus rice straw and fulfill the electricity demand of this village, which had 250 houses with 11.15×10^5 kWh/year of electricity demand (excluding agricultural load). To estimate the amount of surplus rice straw, a survey is conducted on this village, and found that out of 1000-acre, 670-acre (74%) area is under paddy cultivation. The remaining 230 acres (26%) are under vegetables and other crop cultivation. Out of 670 acres, farmers with a paddy cultivation area, 30% (200 acres) prefer the incorporation of rice straw into their fields due to manure benefits and to avoid the balling cost. The Remaining 70% (470 acres) is surplus and burnt directly into fields; these farmers are not ready to bear the cost of balling and incorporation into the field. However, all the farmers are ready to give straw free of cost if the plant can bear the cost of balling and transportation. From the practical experience, it is found that from one acre, after chopping and balling, 2.4 tonnes of straw can be collected. That shows the potential of 1128 tonnes of surplus rice straw annually from 470 acres, as shown in Figure 3.19.

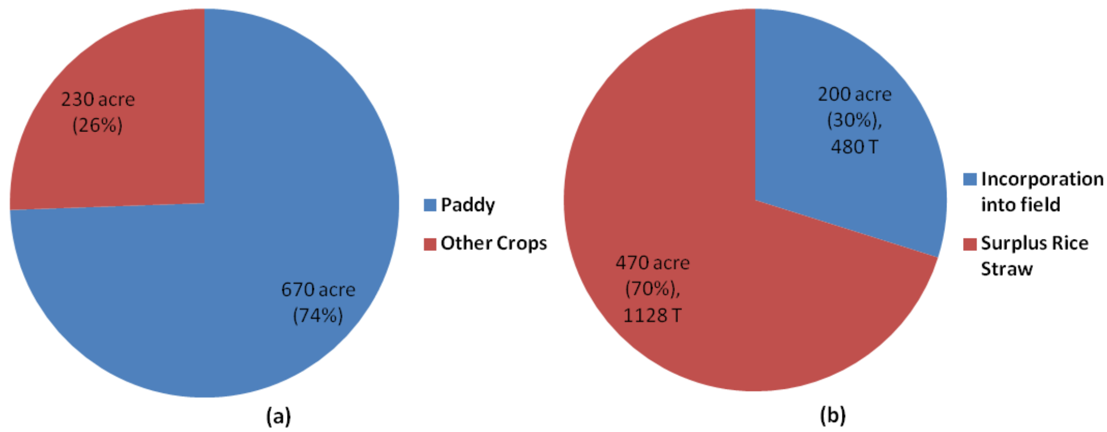

Figure 3.19: (a) Status of paddy cultivation (b) Status of surplus rice straw in the selected region

The village has a peak load demand of 275 kWh and a load factor of 0.463, respectively. In a year, two different load profiles are considered for the summer (March to October) and winter (November to February) seasons, as shown in Figure 3.20.

The detailed load demand of the selected village with 250 houses is given in Table 3.14. The selected site has good solar access of an average 5.76kWh/m^2 per day. Figure 3.20 shows the hourly solar radiation of the selected site for the year.

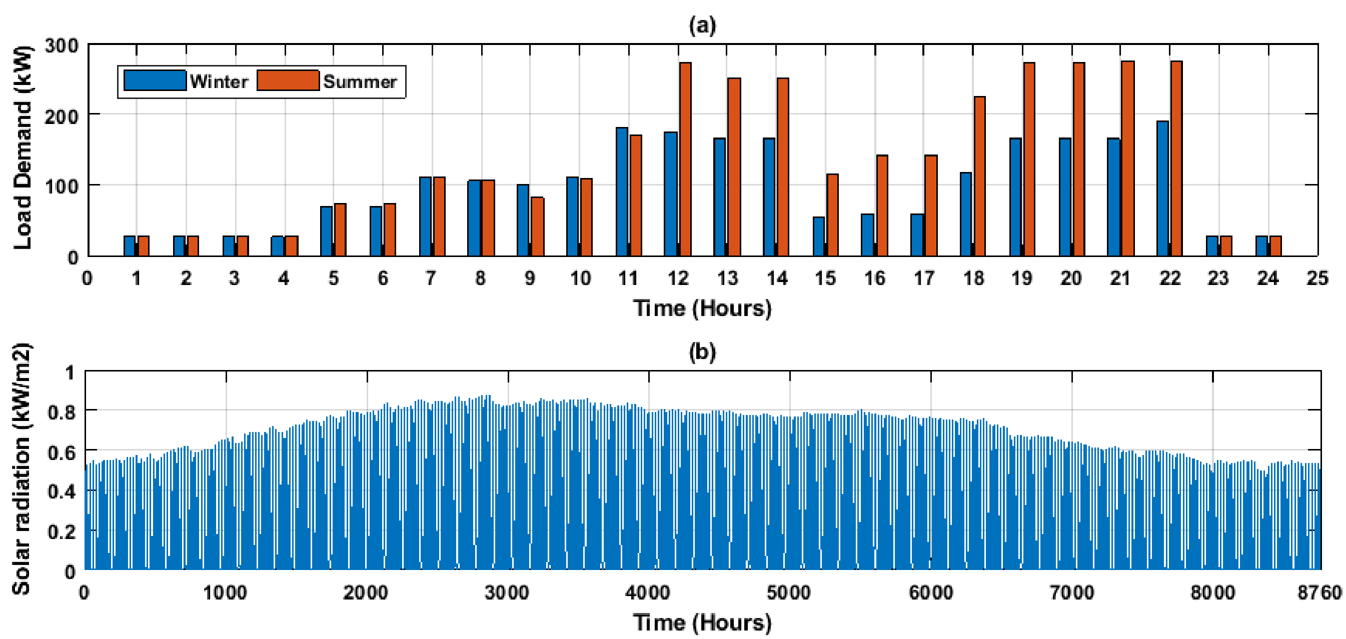

Figure 3.20: (a) Daily load demand of village (b) Solar radiation at the selected region

Table 3.14: Load profile of selected village (250 houses)

Sr. No.	Type Of Load	Quantity	Rating (Watt)	Summer (Mar-Oct)		Winter (Nov-Feb)	
				Hrs/Day	Watt-Hrs/Day	Hrs/Day	Watt-Hrs/Day
	(1) Domestic load demand						
1	Ceiling Fan	6	80	9	4320	0	0
2	LED	10	18	10	1800	9.5	1710
3	CFL	0	27	4	0	3.5	0
4	Television	2	100	9	1800	9	1800
5	Computer	1	300	3	900	5	1500
6	Cooler	2	200	10	4000	0	0
7	Submersible Pump	1	745	0.25	186.25	0.25	186.25
8	Exhaust Fan	2	40	1	80	1	80
9	Water Heater	1	2000	0	0	1	2000
10	Room Heater	2	150	0	0	6	1800
	Total One House				13086.25		9076.25
	Total kWh/Day				13.08		9.07
	Total For 250 Houses kWh/Day				3250		2250
	(2) Community Load Demand						
1	Street Lights	30	30	9	8100	12	10800
2	Shops	10	400	11	10575	11	10575
3	School	1	5000	8	40000	8	40000
4	Small Industry	2	5000	8	80000	8	80000
	Total				138675		141375
	Total kWh/Day				135.67		141.37
	Total Demand (1)+(2) kWh/Day				3385.75		2387.77

3.3.1 System description of rice straw based microgrid

Gasification is the best technology to process rice straw for electricity generation in this area, with an electricity generation potential of 700 kWh/tonne [181]. Considering, the above-mentioned surplus straw and electricity potential, the plant capacity for the gasifier is estimated as 112 kW with a CUF of 80%. The total estimated surplus rice straw from this particular region is not adequate to supply the selected electricity demand. Also, the indoor storage of whole straws for the complete year is not possible or economically not feasible. Weather can affect the system due to outdoor storage and will disturb the feedstock supply chain. So, to increase the reliability of the system and meet the desired load demand, PV and battery storage systems are used to make a microgrid. Different components of the proposed hybrid electricity generation system are shown in Figure 3.21.

Gasifier generating electricity from rice straw is connected AC bus along with the load. To make the system more reliable PV and battery systems are integrated into the system and connected to

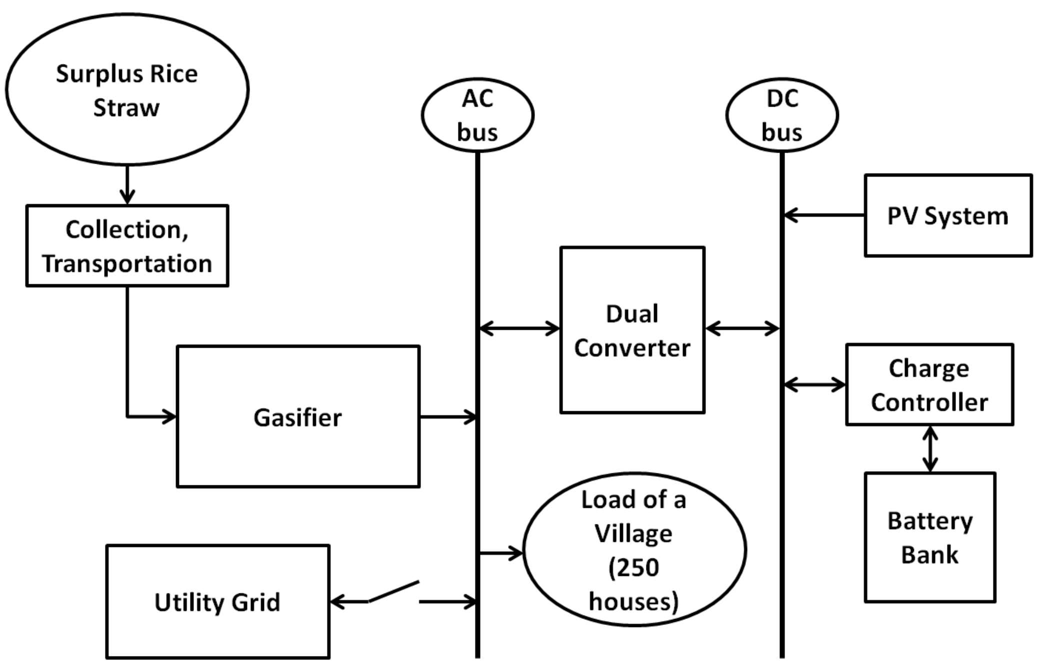

Figure 3.21: Various components of proposed microgrid

the DC bus. To connect the AC and DC bus, a dual converter is used. A charge controller is connected between the battery bank and the DC bus, limiting the charging/discharging rate of the battery bank to keep the power flow smooth. The whole hybrid system is also linked with the main grid so that surplus electricity (when load demand is less) can be sent to the grid, and in crisis (peak demand), electricity can be drawn from the grid. The capacity of the gasifier is kept as per the available amount of surplus rice straw from the selected area in one year. The capacity of PV and battery system is considered by means of optimization of the complete system in standalone mode approaching minimum overall system cost.

3.3.2 Mathematical modelling of the proposed rice straw based microgrid

The numerical modeling of the system mechanism is discussed as follows.

The working experience of a gasification plant in India processing a feedstock with a calorific value of 15 MJ/kg reported 18% efficiency [159]. The calorific value of rice straw is 14 MJ/kg [182]. The maximum installed capacity of the gasifier system (P_{gasi_max}) is obtained as per the amount of spare paddy straw available at the selected region in one year, that is 1128 tonne/year, using equation 3.5. The per-hour output of the gasifier is obtained using equation 3.6. The calorific value of rice straw CV_{bmg} is taken as 14MJ/kg, η_{bmg} biomass to the electricity conversion efficiency of gasifier 18%, CUF 80%. The modeling of PV, battery bank, and converter is taken the same as discussed in section 3.2.

3.3.3 Problem formulation and operational strategy

This study aims to propose an economically optimum and reliable microgrid that can process the surplus rice straw coming from a small village for electricity generation and can meet the load demand of that village. The capacity of the gasifier systems is taken as per the accessible amount of rice straw for this particular location. The PV system and battery bank capacities are the most important result variables that are determined with the help of optimization algorithm and the operational strategy given below.

(a) At any time, if the total power generated from the gasifier and PV is sufficient to fulfill the load demand, then the load is served by these two sources only. If at any time the generated power of PV and gasifier is more than the load demand, then the excess power will be stored in a battery bank that can be represented as

$$P_{b\_ch}(t) = \left(P_{gasi}(t)\right) - (P_{ld}(t) \times \eta_{rec}) + \left(P_{pv}(t)\right) \quad (3.31)$$

where, $P_{b\_ch}(t)$ is battering charging power, $P_{ld}(t)$ is load demand and η_{rec} is the efficiency of the rectifier (90%). P_{pv} is the total power generated by a PV system that can be computed as

$$P_{pv}(t) = P_{sol}(t) \times N_{sol} \quad (3.32)$$

where, N_{sol} is the total number of PV panels.

(b) If at any time $P_{b\_ch}(t)$ is more than the total capacity of the battery bank, the excess power will be sent to the main grid, which can be computed as

$$P_{Gs}(t) = P_{b\_ch}(t) - \left(P_{bmax}(t) - P_{b(t-1)}\right) \quad (3.33)$$

where, $P_{Gs}(t)$ is power sent to the grid, and in the islanded mode, this energy will be the dump energy.

(c) If at any time the power output of PV and gasifier is inadequate to fulfill the load demand, then the balance power will be taken from a battery bank that is calculated as

$$P_{b\_dch}(t) = \frac{\left(P_{ld}(t) - \left(\left(P_{pv}(t) \times \eta_{inv}\right) + P_{gasi}(t)\right)\right)}{\eta_{inv}} \quad (3.34)$$

where $P_{b\_dch}(t)$ is battery discharging power.

(d) If at any time the SOC of the battery bank is not enough to provide the deficient quantity of power means if,

$$P_{b\_dch} > \left(\mathrm{P_b}(\mathrm{t}-1) - \mathrm{P_{b\_min}}(\mathrm{t})\right) \quad (3.35)$$

Then this deficient amount of power will be supplied by the grid as follows

$$P_{Gp}(t) = \mathrm{P_{b\_dch}}(\mathrm{t}) - \left(\mathrm{P_b}(\mathrm{t}-1) - \mathrm{P_{b\_min}}(\mathrm{t})\right) \quad (3.36)$$

where, $P_{Gp}(t)$ is power purchased from the grid and $\mathrm{P_{b\_min}}(\mathrm{t})$ is the minimum power capacity of a battery bank that depends upon the minimum SOC selected. In the present case, the capacity of PV and battery bank is calculated by keeping the microgrid in islanded mode. In islanded mode $P_{Gp}(t)$ will not exist, and a penalty function is used after equation (3.35) to satisfy the load demand with PV, gasifier, and battery bank. The operating strategy is discussed above in a simplified flow chart Figure 3.22.

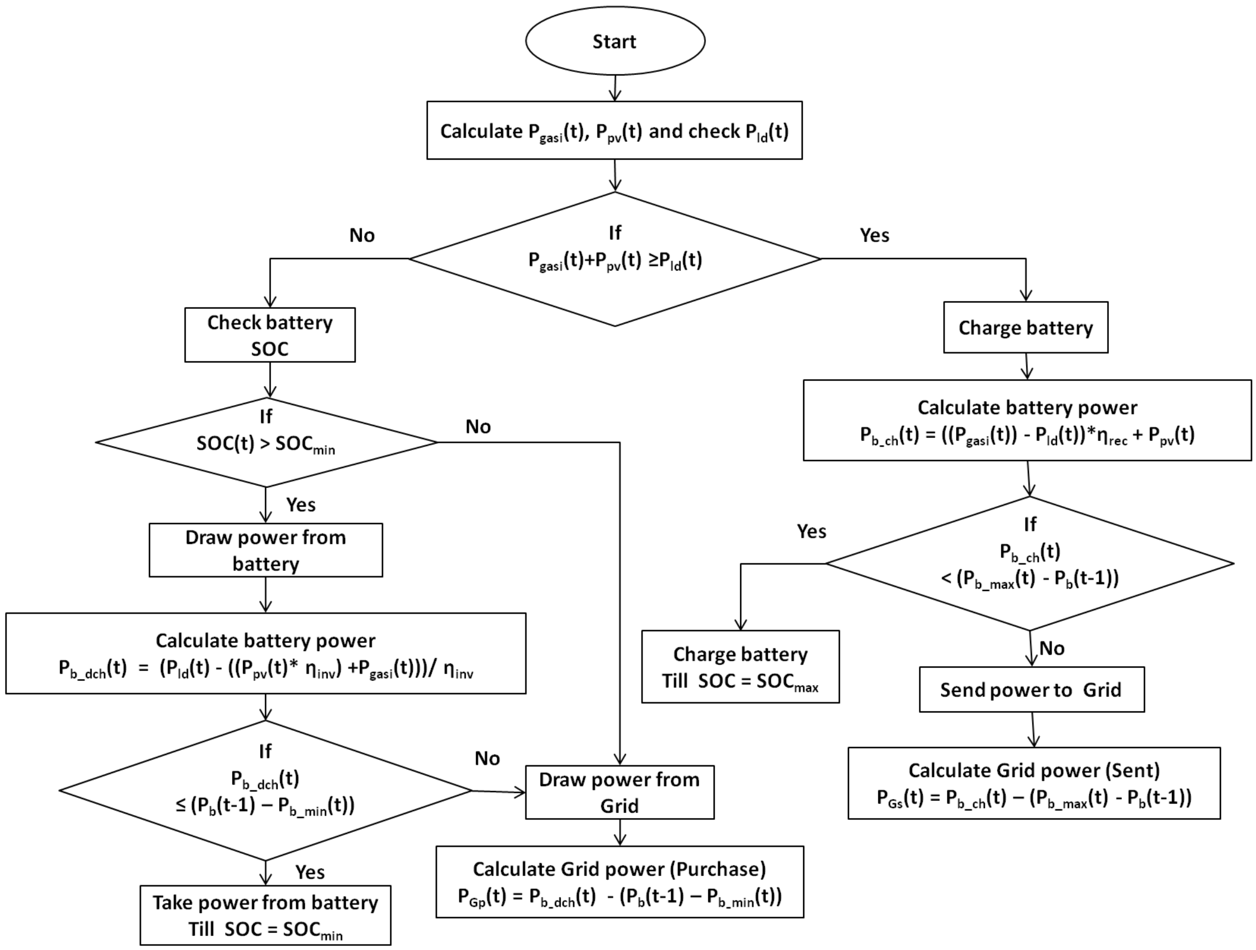

Figure 3.22: Flow chart of operating strategy for the proposed microgrid

3.3.3.1 Objective function and constraints

The aim of optimizing the proposed microgrid system is to minimize the overall cost of the system while maintaining a reliable energy flow. The number of PV panels (N_{sol}) and the number of batteries (N_{batt}) are the main decision variables that will decide the best possible arrangement of the proposed system. The ASC method is used for the economic evaluation of the system. The end result, after fulfilling all the constraints with the least possible ASC, is considered as most excellent.

The objective function of the optimization process is the overall system cost that further consists of capital cost, replacement cost, and operating and maintenance cost of every element integrated to the microgrid. The function given below is taken as the key function that is to be minimized subject to selected constraints.

$$Minimise\ ASC = F\left(\left(P_{gasi} \times C_{gasi}\right) + \left(N_{sol} \times C_{sol}\right) + \left(N_{batt} \times C_{batt}\right) + \left(P_{con} \times C_{con}\right)\right) \tag{3.37}$$

where, C_{gasi}, C_{sol}, C_{batt} and C_{con} are the costs of gasifier (per kW), solar (per kW), battery (per unit), and converter (per kW), respectively.

The ASC of every component has several parts as capital cost$\left(C_{cap}\right)$, replacement cost$\left(C_{rp}\right)$, salvage cost$\left(C_{sl}\right)$, operating and maintenance cost per year$\left(C_{op}\right)$. The total ASC of each component, CRF, constraints, and calculation of LCOE already discussed in section 3.2 (equation 3.20 to 3.30) are used for this system. The size of the proposed system is optimized using the ABC algorithm as shown in Figure 3.23.

3.3.4 Results and discussions of rice straw based microgrid

For the simulation of the proposed hybrid system, Matlab software is used, and the ABC algorithm is adopted to find the optimum result from the proposed methodology. Table 3.15 presents the economic and technical data of all the components considered in the microgrid.

The experimental simulation results are obtained using a time step of one hour on the data set of given input values. The control parameters of the ABC algorithm are shown in Table 3.3. For both the algorithms, the capacity of the gasifier is taken as 112 kW, along with the maximum number of PV panels ($\mathrm{N_{sol\_max}}$) and batteries ($\mathrm{N_{batt\_max}}$) as 1000 and 1400.

The rating of the converter is kept at 275 kW as per peak load demand and is not taken as a decision variable. The total cost of the proposed microgrid consists the cost of the gasifier, PV, battery bank, and converter. The number of PV panels and batteries will affect the final result because all other parameters are fixed. The most optimum result is selected based on ASC and LCOE. Table 3.16 presents the optimized results obtained from the selected algorithm.

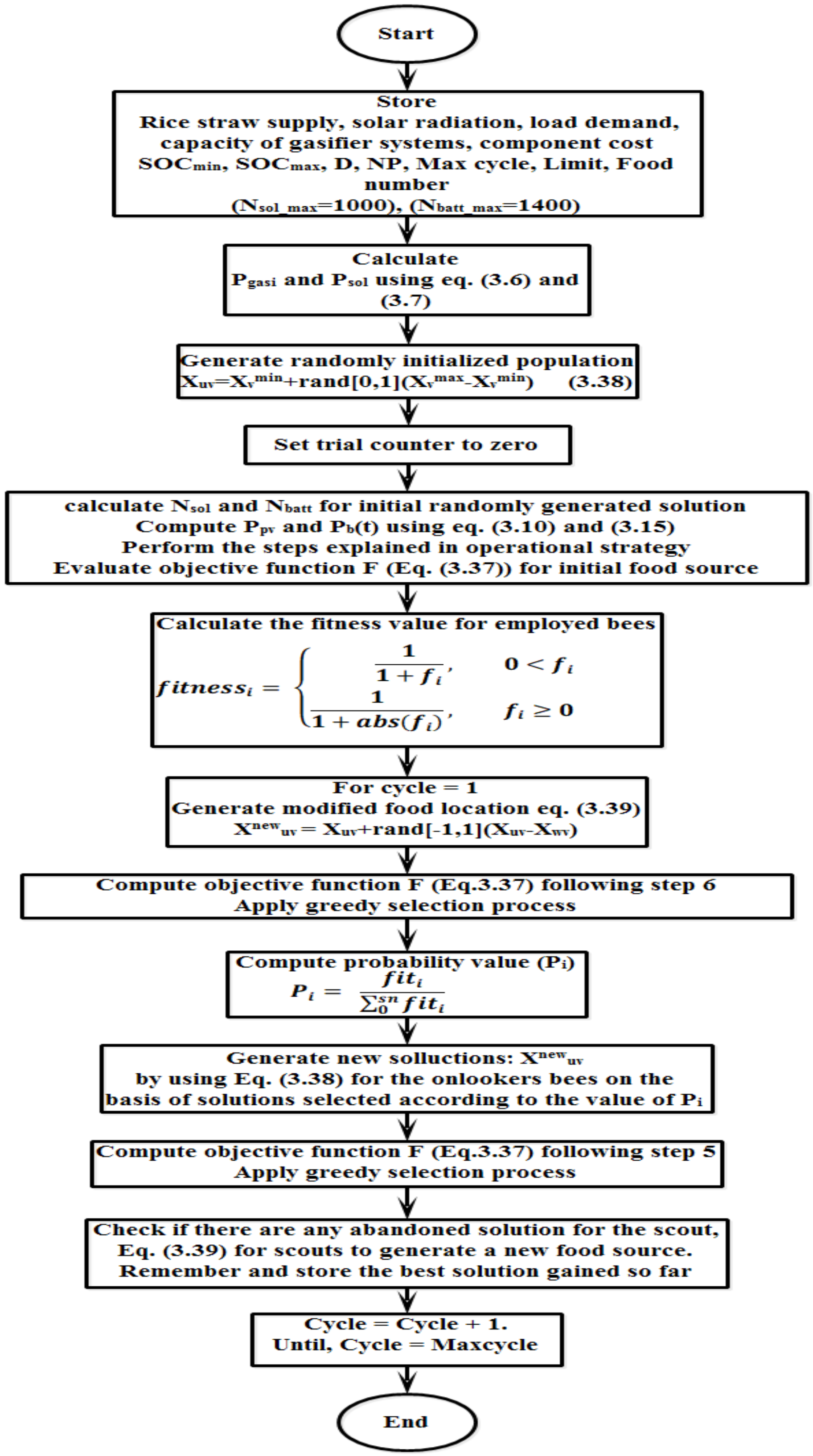

Figure 3.23: ABC algorithm execution

Table 3.15: Economic and technical parameters of selected components

Component	Parameter	Value
Gasifier system	Rated power (kW)	1
	Capital cost (INR/kW)	44285
	O & M cost (INR/kW)	8200
	Replacement cost (INR/kW)	44285
	Fuel cost (INR/tonne of rice straw)	3342.60
	Lifetime (Years)	20
PV	Rated power (kW)	1
	Capital cost (INR/kW)	84000
	O & M cost (INR/kW)	280
	Replacement cost (INR/kW)	84000
	Lifetime (Years)	20
Battery	Capital cost (INR/unit)	11690
	O & M cost (INR/unit)	116.9
	Replacement cost (INR/unit)	4690
	Lifetime (Years)	5
	Nominal voltage (V)	6
	Nominal current (Ah)	360
	Maximum SOC (%)	100
	Minimum SOC (%)	30
Converter	Rated power (kW)	275
	Capital cost (INR/kW)	8890
	O & M cost (INR/kW)	70
	Replacement cost (INR/kW)	8890
	Lifetime (Years)	20
	Efficiency inverter and rectifier (%)	90
	Project life (Years)	20
Others	Interest rate (%)	6
	Bus voltage (V)	120
	Batteries in string (Units)	20

Figure 3.24 shows the conversion rate of the ABC algorithm; the final result is given in just ten iterations. Table 3.16 presents the final ASC and LCOE along with the predicted number of PV panels and batteries. Table 3.17 presents the complete detail of the ASC of the microgrid. The annualized cost of every component is considered using CRF. The components like gasifier, PV panels, and converter have the same lifetime as that of the project, so they didn’t require any replacement. The batteries have a life of 5 years, which is less than the total life span of the project so it needs to be replaced three times. Out of the total cost of the proposed microgrid system, gasifier contributes 53.27%, whereas solar and battery contribute 33.76% and 10.53%.

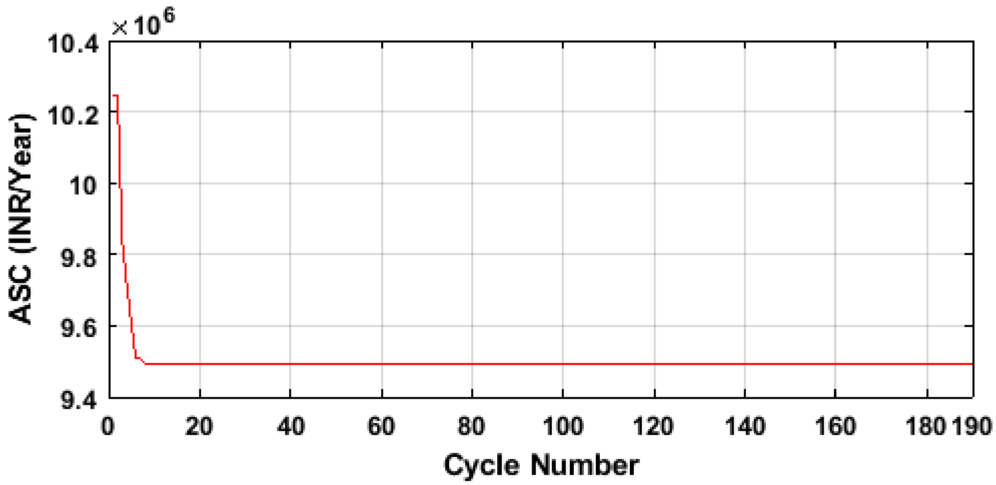

Figure 3.24: Convergence rate of ABC algorithm

Table 3.18 presents the total electricity produced by various sources integrated into the microgrid. The PV system generates more power than the gasifier, and the power sent to the grid is 28% of the total load served. The LCOE of electricity generation technology generally varies from country to country due to various technical, geographical, and policy issues. Table 3.7 shows the global weighted average LCOE of various technologies for the year 2019 [180]. The hydro system is reported as the cheapest power generation system, with a global weighted average LCOE of 0.047 USD/kWh. The weighted average LCOE of the bioenergy system is reported at 0.066 USD/kWh. But for Europe and North America, the bioenergy systems are reported LCOE of 0.08USD/kWh and USD/kWh 0.099, respectively. The LCOE of the proposed system is found to be competitive with the present scenario.

3.3.4.1 Performance analysis of the system during minimum and maximum load demand period

The proposed microgrid consisting of PV, gasifier, and battery bank fulfills the total load demand of one year for the selected village. Figure 3.25 presents the monthly energy balance of the complete year for the proposed microgrid. After satisfying the total load demand, the microgrid has 28% of excess electricity that is sent to the grid. By selecting a time period of two weeks from a year the performance of the microgrid is verified. The first week of January has a minimum load demand, and July that have a maximum load demand is selected.

Table 3.16: Results of selected algorithm for optimal sizing of the hybrid system

Algorithm	Gasifier system (kW)	PV (units)	Battery (units)	Inverter (kW)	ASC (INR/year)	NPC (INR)	LCOE (INR/kWh)
ABC	112	426	701	275	9.60E+6	1.10E+8	6.700

Table 3.17: Complete detail of ASC for the proposed microgrid

Component	Capital cost (INR/yr)	Maintenance cost (INR/yr)	Replacement cost (INR/yr)	Fuel Cost (INR/yr)	Salvage value (INR/yr)	Total cost (INR/yr)
Gasifier	4.33E+5	9.19E+5	------	3.77E+6	------	5.12E+6
PV	3.13E+6	1.19E+5	------	------	------	3.24E+6
Battery	7.15E+5	8.19E+4	2.15E+5	------	------	1.01E+6
Inverter	2.14E+5	1.93E+4	------	------	------	2.33E+5

Table 3.18: Energy analysis of proposed microgrid

Component	kWh/year
Gasifier	7.67E+5
PV	7.87E+5
Battery in	3.14E+5
Battery out	2.79E+5
Load served	1.11E+6
Power to grid	3.14E+5

Figure 3.26 shows the energy balance of the first week of January. In this week, the gasifier runs at 78% of its rated capacity and generates 14700 kWh of electricity. The solar system gives output for nine hours in a day and generates 9785 kWh of total power this week. This week, the

battery supplies 2950 kWh to meet the total load demand of 16709 kWh. After supplying 3207 kWh to battery charging, the system has 6045 kWh of surplus power that is sent to the grid. In this week, the minimum SOC of the battery bank is 73%.

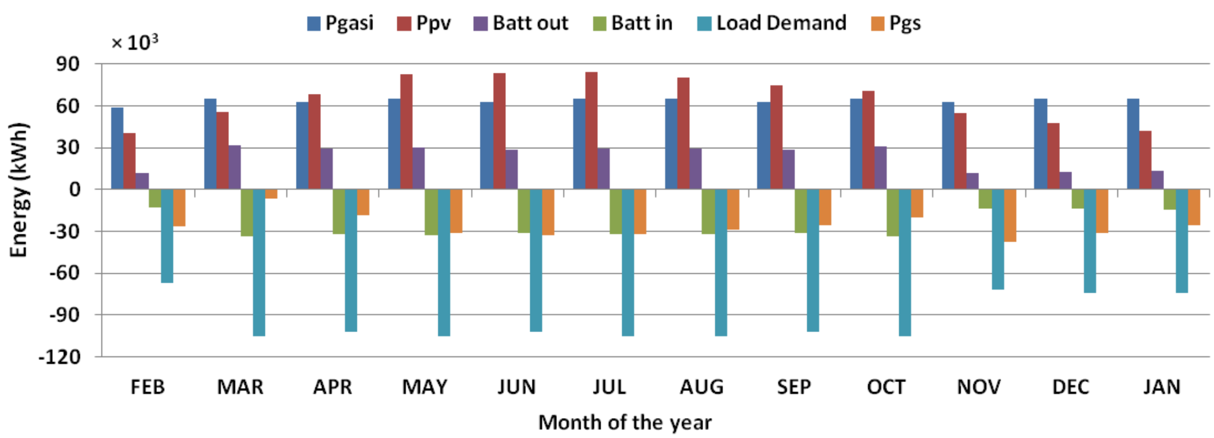

Figure 3.25: Month-wise analysis of power generation from different sources

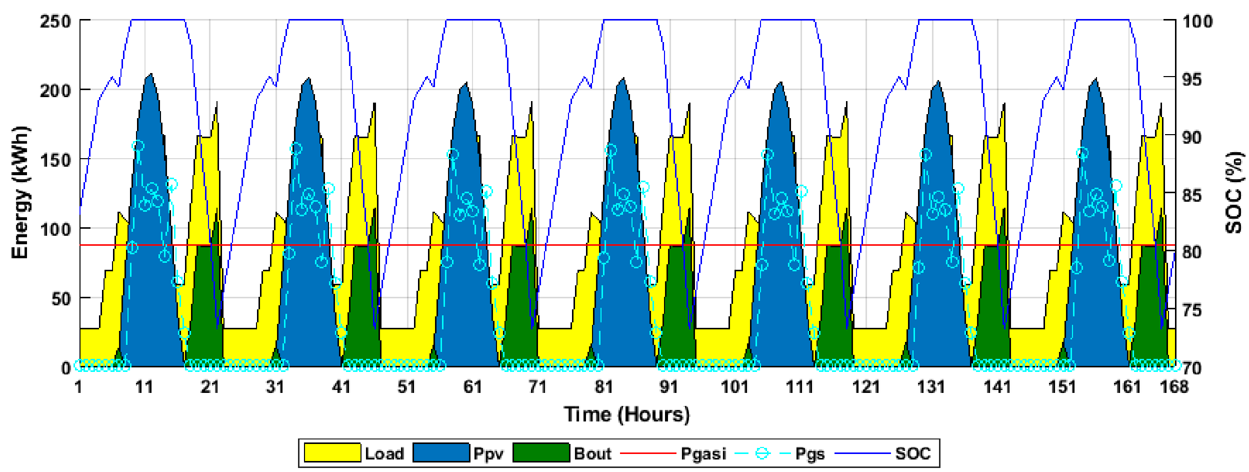

Figure 3.26: Energy balance for the first week of January

In the first week of July, the gasifier runs at 78% of its rated capacity and generates 14700 kWh of power, as shown in Figure 3.27. Due to more irradiation and sunshine hour in summer, the PV system runs for 12 hours in a day and generates 1.94×10^4 kWh of total power in this week, which is more than double compared to winter (January). The battery bank supplies 6.67×10^3 kWh to meet the total load of 2.37×10^4 kWh in this week. After supplying the 7244 kWh to the battery bank for charging, the system has 7522 kWh of surplus power that is sent to the grid. At this time, the minimum SOC of the battery is 38%. As compared to winter in the summer season, PV system generates more power. This time period also has the highest load demand that draws more power from the battery bank, and SOC goes to a minimum level of 38%. As compared to winter, the power sent to the main grid in summers is also higher.

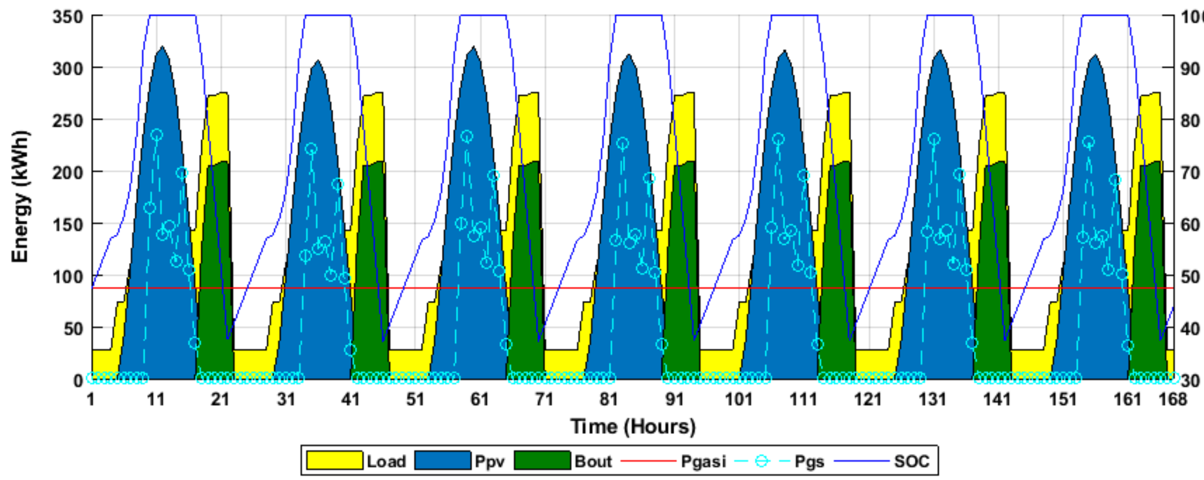

Figure 3.27: Energy balance for the first week of July

3.3.4.2 Sensitivity analysis

For a hybrid system consisting of a battery bank, the measurement of the SOC of a battery is an important issue. Figure 3.28 shows the input and output power of the battery bank for one year along with SOC. The starting and maximum SOC of the battery bank is taken at 100% (1514 kWh), whereas the minimum limit is set at 30% (454 kWh). It can be observed from Figure 3.26 and Figure 3.27 that in winter, SOC remains 73% to 100%, and in summer, most of the time, it remains 38% to 100%. In the initial few hours of March, SOC reached to a minimum level of 30%. Because of increased load and low solar radiation. The limit of charging and discharging current of the battery bank is another important factor. For efficient performance, the maximum charging/discharging power is calculated using equation 3.12 and found to be 231 kWh at 0.15 C-rate. If surplus power coming from generation sources exceeds this limit, then it will be sent to the grid. If at any time deficient power is greater than the discharging limit, then the power will be taken from the grid.

In the case of batteries, another essential parameter is round trip efficiency which affects the LCOE. Presently, the results are obtained by taking round trip efficiency as 92.2%. Figure 3.29 shows the LCOE for different round-trip efficiencies. It can be observed that with an increase in the batteries round trip efficiency, the LCOE decreases significantly.

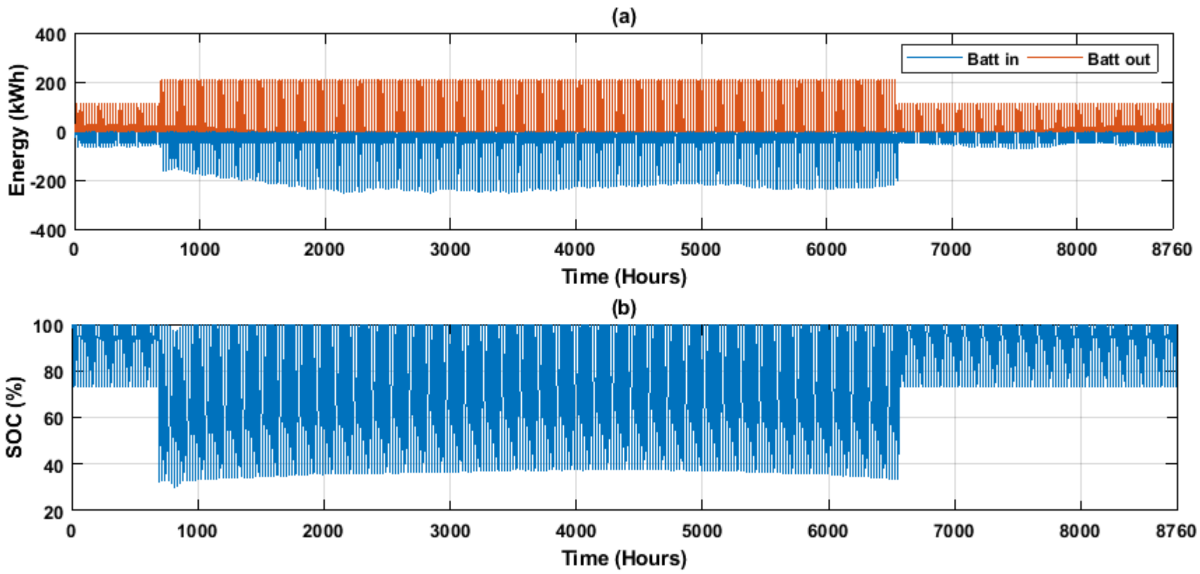

Figure 3.28: (a) Battery charging and discharging power (b) Battery SOC of a complete year

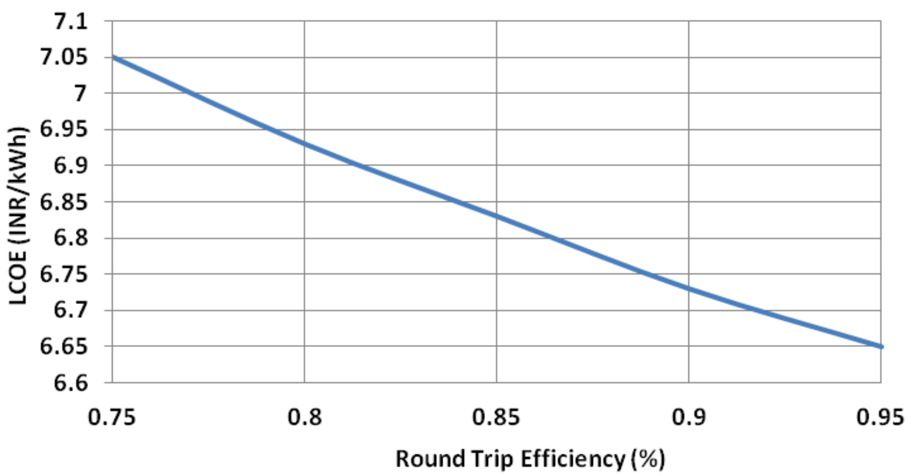

Figure 3.29: Change in LCOE with respect to Battery's round trip efficiency

3.3.4.3 Validation of results of rice straw based microgrid

The PSO algorithm validates the obtained results. The experiment is done on the same dataset data set of input values of one year, considering the same simulation time step of one hour. The control parameters of the PSO algorithm are shown in Table 3.8. The predicted number of PV panels and batteries, along with ASC and LCOE, is shown in Table 3.19. Results show that the PSO algorithm gives the same result for the present problem. So to investigate the reliability and economic factors of the proposed system, the results of the ABC algorithm can be trusted.

Table 3.19: Results of PSO algorithm for optimal sizing of the hybrid system

Algorithm	Biogas system (kW)	Gasifier system (kW)	PV (units)	Battery (units)	Inverter (kW)	ASC (INR/year)	NPC (INR)	LCOE (INR/kWh)
PSO	32	64	260.7	532.5	215	5.77E+6	6.61E+7	5.65

3.3.5 Environmental evaluation

In this section, the proposed microgrid is evaluated for its environmental impacts using the LCA methodology. The adopted methodology (LCA) is discussed prior in section 3.2. The input data related to transportation and preparation of rice straw, its processing by gasification, its open burning emissions along with coal-based electricity emissions is also given in section 3.2.

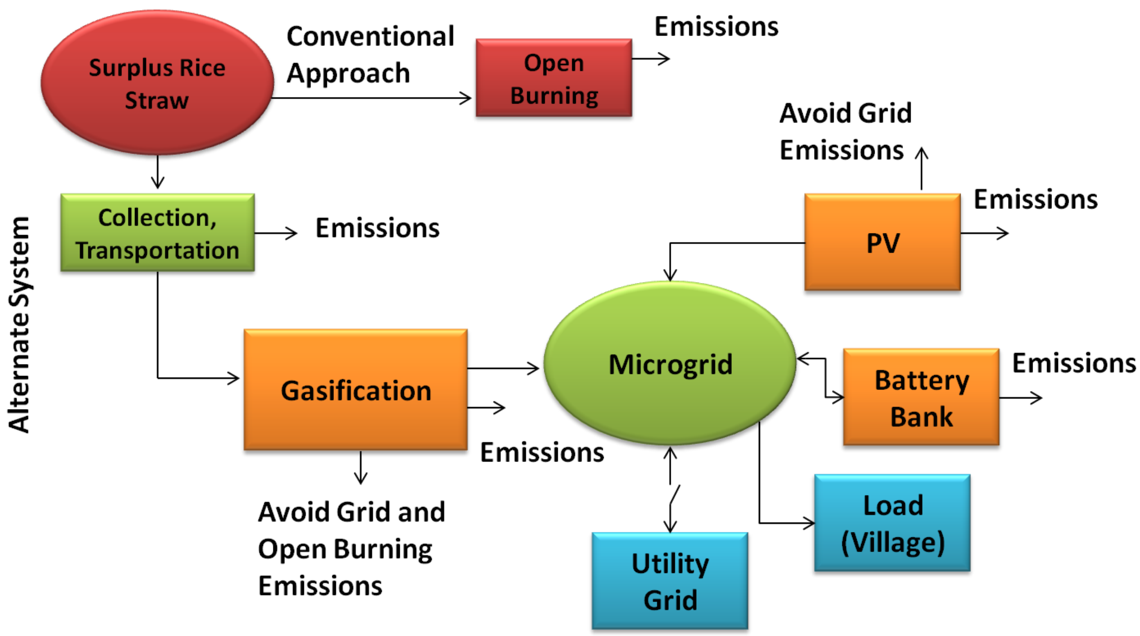

Figure 3.30: System boundaries for the environmental assessment study

Figure 3.30 shows the hybrid electricity generation system boundary. The ecological limit is restricted to the Indian state Punjab, the foremost rice-producing state of India. The system boundary starts with the chopping, balling, and transportation of rice straw and then it's processing by gasification technology to produce electricity. System boundary includes the emissions of rice straw processing by gasification at each stage to the final product produced. As per ISO standards (ISO, 2006) and Renewable Energy Directive (RED, 2009), agricultural crop residues (rice straw) have zero lifecycle emissions till the collection stage [181]. So, environmental impacts from crop growing part are not taken into consideration. For the PV and battery system, only CO_2 emissions during the manufacturing of PV panels and batteries are considered. The electricity produced from the hybrid system is assumed to replace coal-based electricity. System boundary also consists of rice straw open burning emissions as avoided emissions. The emissions related to infrastructure and land used for the system are not considered in this study. Considering the LCA methodology, the environmental impact of the proposed system is evaluated. That is discussed below for the GWP, AP, POCP, and EP categories.

3.3.5.1 Global warming potential

For this category, the proposed hybrid system shows a net reduction of -3.99×10^5 kg CO_2 eq./year. In the net reduction, gasification and PV contribute -2.48×10^6 and -1.53×10^6 kg CO_2 eq./year, as shown in Figure 3.31.

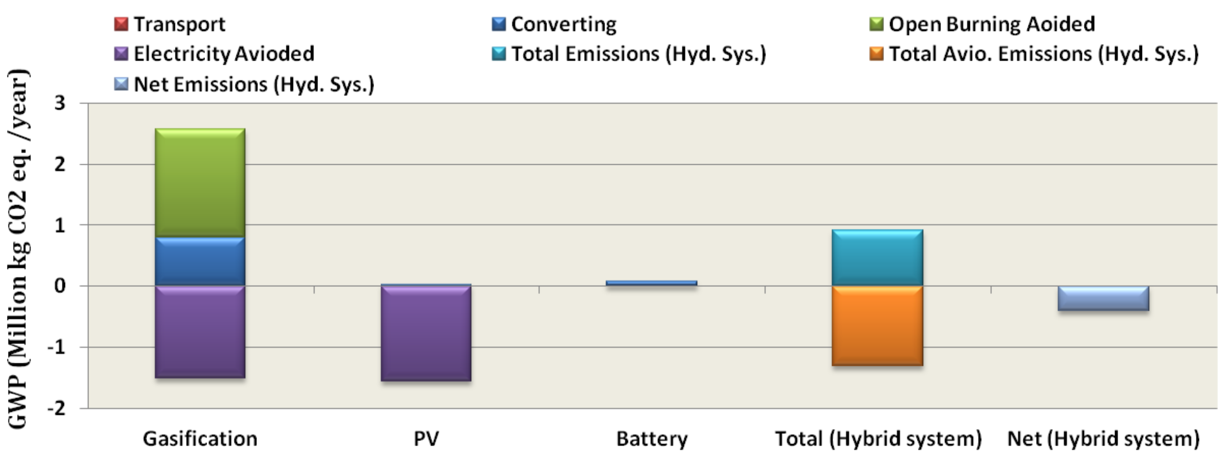

Figure 3.31: GWP impact of proposed microgrid

Gasification due to a larger amount of open burning avoided emissions shows more reduction potential in overall CO_2 emissions than PV. However, the electricity avoided emissions of PV system are more than gasification system. From Table 3.20, it can be noted that the gasification of rice straw shows a significant amount of process emissions as CO_2 and CH_4 emissions along with little CO emissions.

Table 3.20: Emissions from microgrid for GWP category (kg/year)

			CO_2	CH_4	CO	Total CO_2 eq.
Gasification	Process Emissions	Converting	8.04E+5	1.62E+3	1.48	8.05E+5
		Transport	1.12E+2	0.39	2.14	1.14E+2
	Avoided Emissions	Open Burning	-1.65E+6	-3.39E+4	-7.83E+4	-1.76E+6
		Electricity	-9.28E+5	-5.75E+5	-1.38E+4	-1.52E+6
	Net					-2.48E+6
PV	Process Emissions	Manufacturing	3.15E+4			3.15E+4
	Avoided Emissions	Electricity	-9.52E+5	-5.90E+5	-1.41E+4	-1.56E+6
	Net					-1.53E+6
Battery	Process Emissions	Manufacturing	7.82E+4			7.82E+4
	Net					7.82E+4
Net of Microgrid						-3.99E+5

But for the same amount of rice straw that is processed, the open burning avoided emissions are more than double in CO_2, 20 times in CH_4, and a vast amount in CO emissions. The electricity avoided emissions of gasification technology are also more significant than its process emissions, where CO_2 avoided emissions are greater by a significant amount, and CH_4 and CO are greater by a vast difference. For all the selected emissions (CO_2, CH_4, and CO), the preparation and transportation of rice straw contribute by a minimal value. The PV and battery system has some process emissions (CO_2) during manufacturing. But due to the replacement of coal-based electricity, the PV system has huge electricity avoided emissions of CO_2, CH_4, and CO. It can be noted that the rice straw processing technique has a very small installed capacity than PV and higher processing emission, but have very high overall carbon emission reduction tendency than PV. Rice straw processing plant has a great benefit of open burning avoided factor. The open burning of rice straw has high CO_2, CH_4, and CO emissions which are the primary cause of global warming.

3.3.5.2 Acidification potential

For the acidification potential category, the hybrid system shows a net reduction of -1.97×10^4 kg SO_2 eq./year, as shown in Figure 3.32. Here gasification contributes -1.09×10^4 kg SO_2 eq./year, and PV contributes -8.66×10^3 kg SO_2 eq./year in total reduction. Here gasification shows a greater reduction in overall SO_2 emissions than PV.

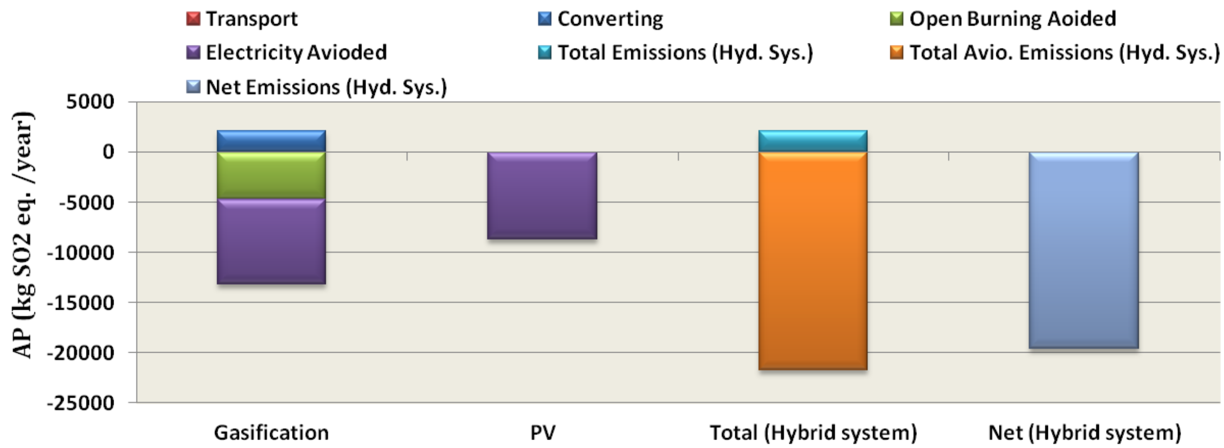

Figure 3.32: AP impact of proposed microgrid

Table 3.21: Emissions from microgrid for AP category (kg/year)

			SO_2	NO_X	Total SO_2 eq.
Gasification	Process Emissions	Converting	14.02	2.13E+3	2.15E+3
		Transport	0.29	0.19	0.48
	Avoided Emissions	Open burning	-2.26E+3	-2.45E+3	-4.70E+3
		Electricity	-5.75E+3	-2.69E+3	-8.44E+3
	Net				-1.09E+4
PV	Avoided Emissions	Electricity	-5.90E+3	-3.93E+3	-8.6E+3
	Net				-8.6E+3
Net of Microgrid					-1.97E+4

The processing of rice straw by gasification has a significant amount of NO_X and a small amount of SO_2 emissions, as shown in Table 3.21. But for the same amount of rice straw that is processed, the open burning avoided emissions are more than by a significant amount in NO_X and very huge amount in SO_2 than its processing emissions. The gasification of rice straw also shows a great tendency for electricity avoided emissions that is even more than its open burning avoided emissions (For both NO_X and SO_2 emissions). That is because coal-based power generation has SO_2 and NO_X emissions that are well-known constituents of this category. The transportation of rice straw has a negligible impact on this category. Due to more electricity generated, the PV system also replaces SO_2 and NO_X emissions of coal-based electricity to a larger extent, even more than gasification.

3.3.5.3 Photochemical oxidation potential

The hybrid system shows a net reduction of -1.69×10^3 kg C_2H_4 eq./year for this category, as shown in Figure 3.33. In this total reduction, gasification contributes -1.25×10^3 kg C_2H_4 eq./year and PV contributes -4.50×10^2 kg C_2H_4 eq./year. In this category, again, gasification reduces more overall C_2H_4 emissions than PV. The processing of rice straw by gasification has a negligible impact on this category by CH_4 and CO_2 emissions, whereas NO_X and VOC emissions emission shows a small impact, as shown in Table 3.22.

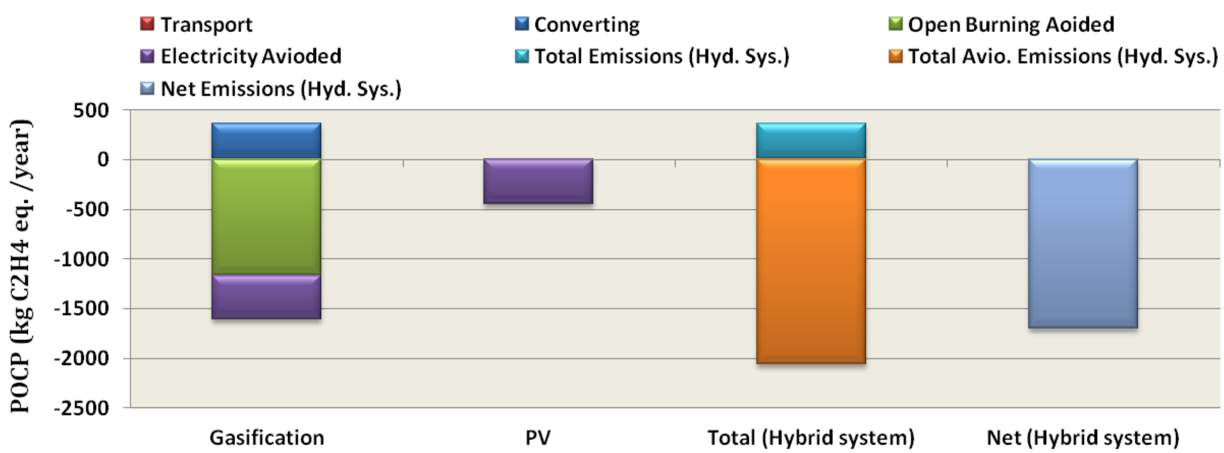

Figure 3.33: POCP impact of proposed microgrid

For the same amount of rice straw processed, the open burning avoided emissions are more than by a significant amount in NO_X and CH_4. Where, the CO open burning avoided emissions are greater by a huge amount than its processing emissions. Compared to processing emissions, the electricity avoided emissions are greater by a significant amount in NO_X and a massive amount in CH_4 and CO. The transportation of rice straw has a negligible impact on this category from all selected emissions. The electricity avoided emissions of PV system are also greater by a significant amount in NO_X and a huge amount in CH_4 and CO. The PV system has no processing emission impact for this category. Also, its electricity avoided emissions are more than gasification. The coal-based power generation has CH_4, CO, and NO_X emissions, mainly contributing to this category.

Table 3.22: Emissions from microgrid for the POCP category (kg/year)

			CH_4	CO	NO_X	VOC	Total C_2H_4 eq.
Gasification	Process Emissions	Converting	0.38	0.02	91.13	270.78	362.32
		Transport	0.95E-4	2.90E-2	0.8E-2		3.7E-2
	Avoided Emissions	Open burning	-8.12	-1.06E+3	-104		-1169
		Electricity	-137.97	-186.25	-114		-439
	Net						-1246
PV	Avoided Emissions	Electricity	-141.60	-191.16	-118		-450
	Net						-450
Net of Microgrid							-1.69E+3

3.3.5.4 Eutrophication potential

For this category proposed system shows a net reduction of -1.06×10^3 kg PO_4 eq./year, as shown in Figure 3.34. In this total reduction, gasification and PV contribute -557 and -511 kg PO_4 eq./year, respectively. For this category, the proposed system has only the NO_X emission that contributes, as shown in Table 3.23.

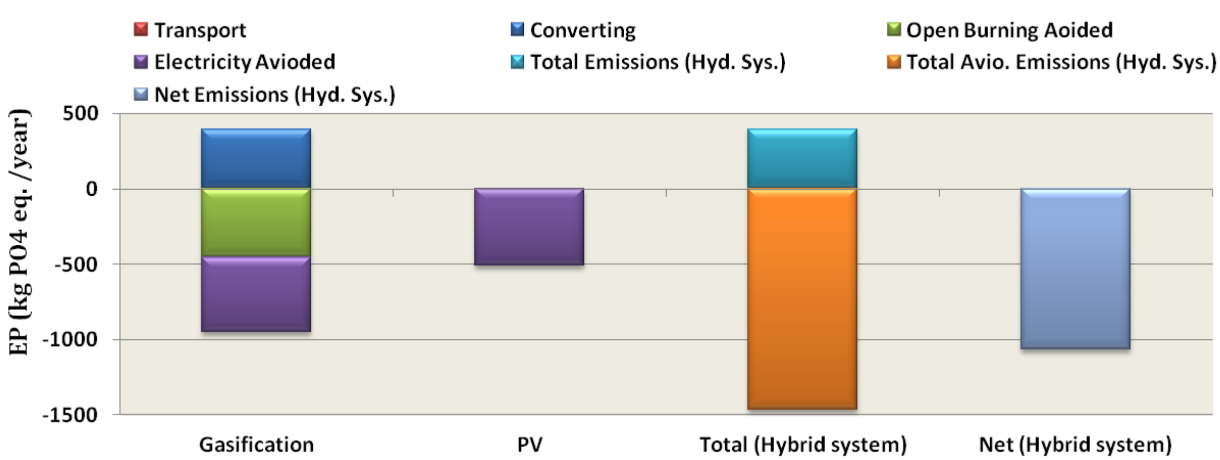

Figure 3.34: EP impact of proposed microgrid

Gasification has a small amount of processing emission as NO_X. The electricity avoided and open burning avoided emissions from gasification are greater by a significant amount for NO_X emissions. Here transportation of rice straw also has a negligible environmental impact. The PV system has no processing emissions for this impact category but shows a significant reduction in overall emissions due to electricity avoided emissions. The electricity avoided emissions of PV system are a little bit more than the gasification system.

Table 3.23: Emissions from microgrid for the EP category (kg/year)

			NO_X	Total PO_4 eq.
Gasification	Process Emissions	Converting	394	394
		Transport	3.55E-2	3.55E-2
	Avoided Emissions	Open Burning	-454	-454
		Electricity	-498	-498
	Net			-557
PV	Avoided Emissions	Electricity	-511	-511
	Net			-511
Net of Microgrid				-1069

3.3.6 Discussions on environmental impact of rice straw based microgrid

The proposed microgrid system is evaluated logically for its environmental impacts. All the technologies integrated with this microgrid system are analyzed individually at each phase of the complete process. Results show that the proposed system has an immense tendency to reduce the pollution of GWP, AP, POCP, and EP environmental categories. With an installed capacity of gasification 112 kW, PV 426 kW, and 1514 kWh of battery storage capacity, the system processes surplus rice straw for electricity generation. The proposed microgrid generates 1429671 kWh/year of electricity with environmental emissions -3.99×10^5 kg CO_2 eq./year, -1.97×10^4 kg SO_2 eq./year, -1697 C_2H_4 eq./year and -1069 kg PO_4/year. The system has per unit of electricity emissions as -0.2970 kg CO_2 eq./kWh, -0.0137 kg SO_2 eq./kWh, -0.0011 C_2H_4 eq./kWh, -0.0007 kg PO_4/kWh. From the comprehensive analysis, it can be noted that the rice straw processing technology gasification has a very small installed capacity in comparison to PV. But its environmental impact reduction tendency for all the selected categories (GWP, AP, POCP, and EP) is higher than PV. Even the gasification of rice straw for electricity generation has processing emissions where PV doesn’t. This shows the significance of waste to energy generation technologies.

Open burning of rice straw has high CO_2, CH_4, and CO emissions that mainly contribute to GWP. These emissions are avoided by the gasification of rice straw, which makes it superior for GWP reduction. The coal-based electricity also has these emissions that are replaced by gasification and PV to a great extent. For AP and EP impact categories, gasification reduces more emission impact due to the replacement of SO_2 and NO_X open burning emissions that contribute to these categories. In the case of electricity avoided emissions for these categories, PV reduces more SO_2 and NO_X Emissions because electricity generated by the PV system is greater than electricity generated by gasification. Similarly, the replacement of CH_4, CO, and NO_X open burning emissions that contribute to the POCP impact category makes gasification superior for this category. The replacement of coal-based electricity emissions by gasification and PV system has also shown a signification reduction impact on the POCP category. Along with the coal-based grid emissions, processing of rice straw for electricity generation also replace the rice straw open burning emissions that have a high tendency to pollute the environment for all selected environmental impact categories. The integration of rice straw processing technologies with other renewable energy generation technologies increases the environmental sustainability of the hybrid system. The proposed rice straw-based microgrid can be a solution to present surplus straw handling environmental problems. Along with the growth of the power system in an environmentally sustainable way, this microgrid could act as a source of income for farmers.

3.4 Chapter summary

A framework for MSW and rice straw-based grid-connected microgrids is proposed in this chapter. In the case of MSW, the microgrid comprises AD, gasifier, PV, and battery system that processes the MSW of a city (population 0.1million) and fulfills the electricity demands of a small village (225 houses). With a per capita waste generation rate of 0.252 kg/person and collection efficiency of 65% city has the potential to install 32 and 64 kW of AD and gasification plants. The ASC of the proposed hybrid system was INR 5.76×10^6 with LCOE 5.65 INR/kWh. The total MSW landfilling avoided cost is 4.52×10^5 INR/year, which is 17% of the cost of its processing cost. The proposed system is also evaluated precisely for environmental impact and found sustainable. For the present case, the combination of AD, gasifier, PV, and battery system could make a gainful and reliable power generation system. In the case of rice straw-based, the microgrid comprises a gasifier, PV, and battery bank. The proposed system processes the surplus rice straw of a small village (250 houses and 900 acres of cultivated land) and fulfills its electricity demand (1.11×10^6 kWh) for one year. The ASC of the proposed hybrid system was found to be INR 9.59×10^6 with LCOE 6.70 INR/kWh. The proposed system is also analyzed precisely for environmental impact and found sustainable. The combination of the gasifier, PV, and battery system is a reliable power generation system. The utilization of surplus rice straw for electricity generation can contribute to the country's sustainable development.

CHAPTER 4

Conclusions

4.1 Conclusions

The study highlights the importance of characteristic assessment (simultaneously in economic and environmental terms) for a particular country for sustainable utilization of MSW and rice straw. Before selecting a technique for processing MSW or rice straw for any country, it is necessary to evaluate and compare the various technologies as per the scenario of that particular country in economic and environmental terms. This study evaluates and compares various MSW and rice straw processing technologies as per the Indian scenario. In India, the potential of energy generation from MSW and rice straw is not adequately utilized and explored. Therefore this study is an effort to propose a framework for sustainable utilization of MSW and rice straw.

As per the analysis conducted in this work, it has been concluded that the AD and gasification technologies are better in economic and environmental aspects than incineration, compost, and RDF to process MSW. For a population size of 0.1 million, AD and gasification show a potential economic value of 1.91×10^4 INR/day and 4.70×10^4 INR/day, respectively. The processing of food waste by AD shows a remarkable reduction in environmental emissions for categories; GWP, AP, POCP, and EP by 123 tonne CO_2 eq./day, 112 kg SO_2 eq./day, 31 kg C_2H_4 eq./day, and 9.80 kg PO_4 eq./day respectively. Whereas the processing of dry waste by gasification reduces shows a remarkable reduction in environmental emissions for categories; GWP, AP, POCP, and EP by 62 tonne CO_2 eq./day, 189 kg SO_2 eq./day, 33 kg C_2H_4 eq./day, and 12.67 kg PO_4 eq./day respectively.

Further, this study proposes a framework for MSW-based grid-connected microgrid comprising AD, gasifier, PV, and battery systems. The system processes the MSW of a city (population 0.1million) and fulfills the electricity demands of a small village (225 houses). With a per capita waste generation rate of 0.252 kg/person and collection efficiency of 65% city has the potential to install 32 and 64 kW of AD and gasification plants. The ASC of the proposed hybrid system was INR 57.60×10^5 with an LCOE of 5.65 INR/kWh. The total MSW landfilling avoided cost is 45.18×10^4 INR/year, which is 17% of the cost of its processing cost. The proposed system is also evaluated precisely for environmental impact and found sustainable. The system shows a negative impact on all selected environmental impact categories (-4.87 kg CO_2 eq./kWh, -0.01155 kg SO_2 eq./kWh, -0.00141 C_2H_4 eq./kWh and -0.0008 kg PO_4/kWh). Therefore present case, the combination of AD, gasifier, PV, and battery system could make a gainful and reliable power generation system.

In the present instance, in the case of rice straw, the production of ethanol by the integrated operation is indicated as the preferred technology as compared to incineration, gasification, AD, and fermentation alone. The integrated operation of AD and fermentation shows economic benefits of 1525 INR /tonne. For electricity production, gasification is preferable as compared to incineration and AD with an economic benefit of 534 INR/day. Further, a framework for rice straw-based grid-connected microgrid that comprises a gasifier, PV, and battery bank is proposed. The microgrid processes the surplus rice straw of a small village (250 houses and 900 acres of cultivated land) and fulfills its electricity demand (11.15×10^5 kWh) for one year. The ASC of the proposed hybrid system was INR 95.94×10^5 with an LCOE of 6.70 INR/kWh. The proposed system is also analyzed precisely for environmental impact and found sustainable. While processing 1128 tonne/year of rice straw, the microgrid generates 14.29×10^5 kWh/year of electricity with environmental emissions of -398888 kg CO_2 eq./year, -19648 kg SO_2 eq./year, -1697.47 C_2H_4 eq./year and -1069.23 kg PO_4/year. The combination of the gasifier, PV, and battery system is an economical and environmentally favorable power generation system.

This study concludes that the utilization of MSW and surplus rice straw for electricity generation can contribute to the country's sustainable development. The rice straw-based microgrid seems to be a reliable source to mitigate the problem of straw management. Along with the utilization of surplus rice straw, it promotes renewable energy-based decentralized electricity generation. The utilization of MSW in a microgrid system will open new doors for its sustainable processing and energy generation. This will save the money spent on landfilling, avoid landfill emissions and reduce the burdens on landfill sites. For hybrid power generation systems, biomass can act as a balancing system to wind and solar resources due to its different properties related to reliability. It is essential in India to make aware the policymakers, investors, and plant developers focus on the sustainable utilization of the MSW and rice straw. The study evaluates the economic and environmental performance of MSW and rice straw processing technologies, which helps decision-makers select the best management strategy with the most negligible impact on the environment.

4.2 Future scope

It is well-documented that renewable energy is the best and simplest solution for reducing carbon emissions. Efficient technologies for proper utilization of DERs, rice straw, and MSW have an excellent future scope as they help maintain environmental and electrical power quality irrespective of environmental constraints. In the future, work can be taken up on simulation studies of microgrid structures (based on rice straw and MSW availability throughout the year) will help draw out future plans for different nature of DGs' installation as per load demand, environmental and capital cost constraints. Simulation work on rice straw and MSW-based microgrid will help in reducing the planning cost. Different combinations of existing technologies in microgrid and conventional power systems can be explored that could help in reducing the capital cost of rural microgrid structures. From simulation case studies, brief outlines for different DERs and rice straw - MSW-based DGs can be drawn to maximize benefits from the available DERs. Further, with the real-time implementation of rice straw - MSW-based DGs and DERs, the losses will be minimized for scattered load distribution. Scattered load demand being fed by MSW and rice straw-based DGs can further open a vast area of research on switching from microgrid to nano grid consisting of small rice straw-MSW DGs feeding individual domestic loads of the range of 5 – 50 kW.

In the case of hybrid electricity generation systems, the control and feasibility in terms of voltage and frequency variations under fault conditions are sensitive issues that can be explored in the future for the proposed system. Pilot-scale plants and experiments are required to intend and define the operational parameters for farm-scale waste to energy generation plants. The feasibility study for MSW and rice straw-based hybrid microgrids with fuel cells and vertical wind turbines could also be explored. The proposed systems and the research outcomes are limited to the Indian scenario. The author will try to set up a small-scale practical hybrid system proposed in this study for experiments and benchmarking the various technical parameters.

4.3 Limitations, assumptions, weaknesses and recommendations of proposed research work

This study does not include the effect of any natural disaster like floods and storms that may affect the feedstock supply chain. The geographical boundary of the present study is limited to an Indian state- Punjab. The results may vary for any other location. The numeric figures are rounded off to two decimal points that may contain an approximate 5% round-off error. For any other country, the choice of MSW and rice straw processing technologies should be made after a comparative analysis of various technologies. Similarly, the integration of other renewable technologies should be as per a particular location's available sources and weather conditions. The load of the selected villages is based on the survey that may be different for some other time. This research is confined only to a data structure of one year. Therefore did not consider any variation in load demand in the future. In order to have the actual implementation of the current study, the factors like an increase in load for a complete lifetime of a power generation plant (generally 20 years) should be estimated.

All the economic parameters of selected technologies were taken as per the policies and directions of the planning commission of the Indian Government, which may vary in upcoming years. There is a great cultural diversity in different Indian states, due to which there is variation in their food habits that alter the category of MSW available. Based on the aforementioned conditions, the author recommends a critical analysis of MSW available for any particular location where anybody wants to apply the research. This study did not include the loss of load probability during the modeling and simulation of the microgrid. The proposed study does not consider any disturbance in voltage and frequency under fault conditions.

The Indian Government has offered subsidies through various policies for waste to energy generation plants. Depending upon the technology, different tariff rates are also offered for the sale of electricity to the electricity authority of the state. In the case of hybrid energy generation systems, no such scheme clarifies the subsidy and tariff rate for these systems. Thereby posing a hindrance in the implementation of such systems in India. The success rate of MSW in energy generation plants in India is not up to the mark. The presence of a high percentage of food waste (35%) in Indian MSW and improper segregation are the major barriers in the development of these plants. For a single technology like incineration, gasification, and AD, it is very difficult to maintain the feedstock and its supply chain with such a percentage of wet MSW and seasonal variations. It is necessary to implement a policy in India that clarifies the tariff rates and subsidies related to these types of hybrid plants for the private sector. The Government has to offer funding and land for municipal authorities to establish their processing plants. Also, the landfill saved credits should be considered along with the carbon credits. While expanding the power system for electricity demand of rural areas, the possibility of these types of hybrid systems should be taken as an essential matter.

The actual implementation of this research can solve the many problems related to waste management of MSW and rice straw along with sustainable power generation.

List of publication based on thesis work

Science Citation Indexed (SCI) Papers:

1. Singh, A., & Basak, P. (2018). Economic and environmental evaluation of municipal solid waste management system using industrial ecology approach: Evidence from India. *Journal of Cleaner Production*, *195*, 10-20.**(Impact Factor 9.29)**
2. Singh, A., & Basak, P. (2019). Economic and environmental evaluation of rice straw processing technologies for energy generation: A case study of Punjab, India. *Journal of Cleaner Production*, *212*, 343-352. **(Impact Factor 9.29)**
3. Singh, A., & Basak, P. (2021). Conceptualization and techno-economic evaluation of microgrid based on PV/Biomass in Indian scenario, *Journal of Cleaner Production*, 317,128378. **(Impact Factor 9.29)**
4. Singh, A., & Basak, P. "Conceptualization and techno-economic evaluation of municipal solid waste based microgrid, Energy, Volume 238, Part B, 2022, 121711**. (Impact Factor 7.14)**

Book chapter:

1. Singh, A., & Basak, P. Present Energy Scenario and need of Microgrid in India, Foundations and Frontiers in Computer, Communication and Electrical Engineering, Acharyya (Ed.) © 2016 Taylor & Francis Group, London, ISBN: 978-1-138-02877-7.

Non SCI Papers:

1. Singh, A., Basak, P., Modelling and Simulation of Building Integrated Photovoltaic (BIPV) System for Energy Efficient Buildings, International Journal of Computer Applications IJCA Proceedings on International Conference on Advancements in Engineering and Technology (ICAET 2016 - Number 8):975-8887 · September 2016.

Conference Papers:

1. Singh, A., & Basak, P. Modelling and simulation of PV-biogas based power generation system and its scopes of industrial applications: A case study on Punjab in India, 7th IEEE India International Conference on Power Electronics IICPE2016.

Appendix A

Supplementary Material to **Chapter 2, section 2.3** “Evaluation of MSW processing technologies”.

Table of Contents

1) Product And Product Value Of Alternative Techniques

a) AD

1m^3 of biogas with 60% methane can produce 2 kWh of usable electricity [122]. In present case the biogas yield of MSW is 55 m^3 per tonne [123]. That has potential of 110 kWh/tonne. As per report given by the municipal corporation Pune an AD plant of 5 tpd capacity can produce 150 tonne of compost annually that is 8.2% of the total feedstock processed [125]. Ministry of New and Renewable Energy Resources, Government of India, provided tariff rates of electricity for AD is INR 7.60 per unit [124]. The price of compost produced by AD is INR 1200 per tonne [125].

Feedstock available for AD = 84 tonne/day

Electricity produced = 84*110 = 9.24 MWh/day

Compost produced = 84*0.082 = 6.9 tpd

Product value from electricity = 9240*7.60 = 70224 INR/day

Product value from compost = 6.9*1200 = 8280 INR/day

Total product value = 70224+8280 = 78504 INR/day

b) Compost

As per [133] India has an estimated potential of producing about 4.3 million tons of compost each year considering population 330 million, per capita generation of wastes as 0.376 kg, compostable matter in the wastes as 42% and average collection efficiency as 70%. Price of compost is INR 2500 per tonne [124].

MSW generated per day = $330*10^6*0.376$ = 124080000 kg

MSW collected per day = 124080000*0.70 = 868560000 kg

Compostable MSW = 868560000*0.42 = 364795200 kg = 36479.52 tonne/day

Compost produced per day = $(4.3*10^6)/365$ = 11780.82

Percentage of MSW = (11780.82/36479.52)*100 = 32.28%

In present study MSW available for composting = 84 tonne/day

Compost produced = 84*0.3228 = 28 tonne/day (approximately)

Product value = 28*2500 = 70000 INR/day

c) RDF

In Indian scenario 750 tonne of RDF can be produced from 1300 tonne of MSW [138]. Price of RDF is1500 per tonne [124].

Percentage = (750/1300)*100 = 57.59%

MSW available for RDF plant = 76.08 tonne/day

RDF produced = 43.89 tonne/day

Product value = 43.89*1500 = 65835 INR//day

d) Gasification

From a practical experience Municipal Corporation of Pune reported power generation of 2.5 MW per day from 250 tonne of MSW [147] with a potential of 240 kWh/tonne. Tariff rates of electricity for gasification is INR 6.50 per unit [124].

MSW available for gasification = 76.08 tonne/day

Electricity produced = 76.08*240 = 18.25 MWh/day

Product value = 18250*6.50 =118684.8 INR//day

e) Incineration

Power potential of incineration in India is reported 167 kWh/tonne with a net electrical efficiency of 15% [60]. Tariff rate of electricity for incineration is INR 6.50 per unit [124].

MSW available for incineration = 76.08 tonne/day

Electricity produced = 76.08*167 = 12.7 MWh/day

Product value = 12700*6.50 = 82550 INR//day

2) Transportation Avoided Cost

Transportation costs are calculated as per method reported in [183]

Mileage of truck = 4.5 km/litre

Diesel price = INR 59.2 per litre as on Jan. 16, 2017 in India

Therefore, fuel cost per kilometer = INR 13.15

Maintenance cost = INR 150000/year

Distance traveled in one year = 43800 km (as per given reference the distance traveled in one day = 120 km)

Maintenance cost of each truck per km = 150000/43800 = INR 3.42/km

Distance travelled to landfill site (round trip) = 40 km

Number of trips per day by each truck = 3

Total distance travelled by each truck = 120 km/day

Cost of fuel = INR 13.15*120 = 1578 INR/day

Maintenance cost of each truck = 3.42*120 = 410.4 INR/day

Salary of one driver = INR 10000/month

Drivers required = 3

Total salary = INR 30000/month

Salary per day = INR 1000

Capacity of truck = 12 tonne

Total MSW handled by each truck = 36 tonne/day

Cost of transporting 36 tonne per day = 1578+410.4+1000 = INR 2988.4

Cost of transporting one tonne per day to a landfill site = 2988.4/36 = INR 83

Transportation avoided cost for all alternatives are

a) AD = 84*83 = INR 6972
b) Compost = 84*83 = INR 6972
c) RDF = 76.08*83 = INR 6314.64
d) Gasification & Incineration = 76.08*84.17 = INR 6314.64

3) Landfill Avoided Cost

Construction cost of capacity 500 TPD for 6 years is INR 13 Crore as per [107]

Construction cost per day for 500 tonnes of waste = 130000000/6/365 = 59360.73

Construction cost per tonne per day = 59360.73/500 = INR118.72

O & M cost = 0.7% of capital cost/year as per [60]

O & M cost per year = INR 910000

O & M cost per tonne per day = 910000/365/500 = INR 4.986

Total cost of landfilling one tonne per day = 118.72 + 4.986 = INR 123.7

Total cost of 240 tonne per day = 123.7*240 = INR 29688

Then avoided cost for alternative technologies will be

a) AD = 84*123.7 = INR 10390.8
b) Compost = 84*123.7 = INR 10390.8
c) RDF = 76.08*123.7 = INR 9411.09
d) Gasification = 76.08*123.7 = INR 9411.09
e) Incineration = 76.08*123.7 = INR 9411.09

4) Alternative Transportation Cost

a) AD

As per the calculations done in section 2

Fuel Cost per kilometer = INR 13.15

Maintenance cost of each truck per km = INR 3.42/km

Salary of drivers per day = INR 1000

Distance travelled for AD plant (round trip) = 20 km

Number of trips by each truck = 3

Total distance travelled by each truck = 60 km

Cost of fuel = 13.15*60 = INR 789/day

Maintenance cost per day = 3.42*60 = INR 205.2

Capacity of truck = 12 tonne

Total MSW handled by each truck = 36 tonne/day

Cost of transporting 36 tonne per day = 789+205.2+1000 = INR 1994.2/day

Cost of transporting one tonne per day = 2015.2/36 = INR 55.39/day

Cost of transporting 84 tonne per day = 84*55.97 = 4652.76/day

b) Compost & RDF

Distance travelled (round trip) = 40 km

Fuel Cost per kilometer = INR 13.15

Number of trips by each truck = 3

Total distance travelled by each truck = 120 km

Cost of fuel = INR 13.15*120 = INR1578

Maintenance cost of each truck = INR 3.42/km

Maintenance cost of each truck per day = 3.42*120 = INR 410.4

Salary of drivers per day = INR 1000

Cost of transporting 36 tonne per day = 1578+410.4+1000 = INR 2988.4

Cost of transporting one tonne per day = 2988.4/36 = INR 83

Cost of transporting 76.08 tonne per day (for RDF) = 83*76.08 = INR 6314.64

Cost of transporting 84 tonne (for compost) tonne per day = 83*84 = INR 6972

c) Gasification & Incineration

Distance travelled (round trip) = 80 km

Fuel Cost per kilometer = INR 13.15

Number of trips by each truck = 3

Total distance travelled by each truck = 240 km

Cost of fuel = INR 13.15*240 = INR 3156

Maintenance cost of each truck = INR 3.42/km

Maintenance cost of each truck per day = 3.42*240 = INR 820.8

Salary of drivers per day = INR 1000

Cost of transporting 36 tonne per day = 3156+820.8+1000 = INR 4976.8

Cost of transporting one tonne per day = 4976.8/36 = INR 138.24

Cost of transporting 76.08 tonne per day = 138.24*76.08 = INR 10517.29

5) Shredding Cost

As per [184] the shredder manufactured by Chudekar Agro Engg. Pvt. Litred. (Mumbai) costs 125000, life 10-15 years, capacity 1 tonne/hour and power rating 7.46 KW

Considering life 10 years maximum 87600 tonnes can be processed

Capital cost of processing one tonne = 125000/87600 = INR 1.42

Operating cost for one tonne = 7.46*5.5 = 41.03 (per unit rate of power consumed by shredder is assumed INR 5.5 for all technologies)

Total shredding cost for one tonne = 1.42 + 41.03 = INR 42.45/tonne

Shredding cost for AD = 84*42.45 = INR 3565.8

Shredding cost for compost = 84*42.45 = INR 3565.8

Shredding cost for RDF = 76.08 *42.45 = INR 3229.59

Shredding cost for gasification & incineration = 76.08 *42.45 = INR 3229.59

6) Converting Cost

a) AD Converting Cost

As per [121] Capital cost = 40.25 crore, capacity 300 tpd, operating and maintaince costs = 2.72 crore/year

Assuming investment was spread over 20 years and 365 days per year gives an average of = INR 55136/day

Quantity processed in one day = 300

Cap. Cost of processing one ton per day = 55136/300 = INR 183.78

Cap Cost of processing 84 tonne per day = 183.78*84 = INR 15437.52/day

O & M cost = 27200000/year = 74520/day/300 tonne = INR 248.40/day/tonne

O & M of 84 tonne per day = 248.40*84 = INR 20865.7/day

AD total cost /day = Cap. Cost /day + O & M cost/day = INR 36303.22/day

b) Compost Converting Cost

as per [132] Capital cost = INR 28.34 crore

Capacity = 200 tpd

O & M cost = INR 2.32 crore/year

Assuming investment was spread over 20 years and 365 days per year gives an average of = 38821/day

Capital cost per tonne per day = 8904.10/200 = INR 194

Cap Cost of processing 84 tonne per day = 84*194 = INR 16305

O & M cost = INR 2.32crore/year = 63561/day/200 tonne = INR 317.8/day/tonne

O & M per day = 84*317.8 = INR 26695.8/day

Compost total cost/day = Cap. Cost /day + O & M cost/day = INR 43000/day

c) RDF Converting Cost

In general investment costs are in the range of INR 140 – 370 per ton for annual capacities of 45,000 to >500,000 tons of input MSW as reported in [185]. The lower costs apply to larger facilities. Operation and maintenance costs are in the range of INR120 – 290 per ton. Considering capital cost INR 255/tonne, operating and maintaince cost INR 205/tonne.

Capital cost = INR 255/tonne

O & M Costs = INR 205/tonne

Capital cost for 76.08 tonne per day = 255*76.08 = INR 19400.4

O & M of 76.08 tonnes per day = 205*76.08 = INR 15596.4

RDF total cost/day = Cap. Cost /day + O & M cost/day = INR 34996.8

d) Gasification Converting Cost

Capital cost = INR 15.57 crore/MW, life 20 year, O & M costs = 5.82 % of capital cost/year as per [136]

O & M costs = 155700000*0.0582 = INR 9061740/year

Capacity = 250 TPD for 2.5 MW as per [147]

For 1 MW 250/2.5 = 100 tpd

Assuming investment was spread over 20 years and 365 days per year gives an average of = 21328.76 INR /day

Quantity processed in one day = 100 tonne

Cap. Cost of processing one ton per day = 21328.76/100 = INR 213.28

Cap. Cost of processing 76.08 tonne per day = 213.28*76.08 = INR 16226.34/day

O & M cost = 9061740/year = 24826.68/day/100 tonne = 248.26/day/tonne

O & M of 76.08 tonnes per day = 248.26*76.08 = Rs 18889.12/day

Gasification total cost/day = Cap. Cost /day + O & M cost/day = INR 35115.48/day

e) Incineration Converting Cost

Capital cost = 60 crore, capacity 700 tpd, operating and maintaince costs = INR 3 crore/year, plant life 15 years as per [121]

Assuming investment was spread over 15 years and 365 days per year gives an average of = INR 109589.04/day

Quantity processed in one day = 700 tonne

Cap. Cost of processing one ton per day = 109589.04/700 = INR156.55

O & M cost = 3 crore/year = 82191.78/day/700 tonne = 117.41/day/tonne

Total cost for one tonne per day = Cap. Cost /day + O & M cost/day = INR 273.96

RDF total cost for 76.08 tonne/day = Cap. Cost /day + O & M cost/day = INR 20843.39/day

7) Residue Cost

Cost of transporting MSW to a landfill site = INR 83/tonne (calculated in section 2)

Cost of landfill = INR 123.7/tonne (calculated in section 3)

Total cost of residue = 123.7+83 = INR 206.7/tonne

Residue for AD = total quantity of MSW – quantity of MSW processed = 240 -84 = 156 tonne

Residue cost for AD = 156*206.7 = INR 32245.2

Residue for compost = 240 -84 = 156 tonne

Residue cost for compost = 156*206.7 = INR 32245.2

Residue for RDF = 240-76.08 = 163.92

Residue cost for RDF = 163.92*206.7= INR 33882.26

Residue for gasification = 240-76.08 = 163.92

Ash produced by gasification = 76.08*0.3 = 22.82 tonne/day (considering 70% volume reduction as reported 50-90% in [116])

Total residue for gasification = 163.92+22.82 = 186.74 tonne/day

Residue cost for gasification = 186.74*206.7 = INR 38590.89

Residue for incineration = 240-76.08 = 163.92

Ash produced by incineration = 76.08*0.10 = 7.6 tonne (considering 90% volume reduction as per [116])

Total residue for incineration = 163.92+7.6 = 171.5 tonne

Residue cost for incineration =171.5*206.7= INR 35449.05 tonne

8) Transportation Emissions From Alternative Technologies

Emission factors for transport are calculated as per the emissions factors for trucks given in [100].

Table 1: Transport emissions/ km

CO_2	CH_4	CO	NO_X	SO_2	PM
0.5122	0.00009	0.0036	0.0063	0.00142	0.00028

a) AD transportation emissions

Waste to handle = 84 tonne

Distance for one round trip = 20 km

Capacity of truck = 12 tonne

Trips required = 84/12 = 7/day

Total km to travel = 20*7 = 140 km/day

Table 2: AD transport emissions /day

CO_2	CH_4	CO	NO_X	SO_2	PM
71.708	0.0126	0.504	0.882	0.1988	0.0392

b) Compost transportation emissions

Waste to handle = 84 tonne

Distance for one round trip = 40 km

Trips required = 84/12 = 7 trips/day

Total km to travel = 40*7 = 280 km/day

Table 3: Compost transport emissions /day

CO_2	CH_4	CO	NO_X	SO_2	PM
143.416	0.0252	1.008	1.764	0.3976	0.0784

c) RDF transportation emissions

Same as compost due to same amount of waste and distance

d) Gasification transportation emissions

Waste to handle = 76.08 tonne/day

Distance for one round trip = 80 km

Trips required = 76.08/12 = 6.34 = 7 trips/day

Total km to travel = 7*80 = 560 km/day

Table 4: Gasification transport emissions /day

CO_2	CH_4	CO	NO_X	SO_2	PM
286.832	0.0504	2.016	3.528	0.7952	0.1568

e) Incineration transportation emissions

Same as gasification due to same amount of waste and distance

9) Shredding Emissions

Table 4: Grid emissions (mix) for northern grid [101]

kg/kWh	CO_2	CO	CH_4	NO_X	SO_2	PM	VOC
	1.11	0.00117	0.00445	0.00223	0.00277	0.003139	1.01E-07

As per [184] the shredder manufactured by Chudekar Agro Engg. Pvt. Litred. (Mumbai), capacity 1tonne/hour and power rating 7.46 KW

a) AD shredding emissions

MSW processed = 84 tonne/day

Electricity consumed by shredder = 7.46*84 = 626.64 kWh/day

Table 5: AD shredding emissions /day

CO_2	CO	CH_4	NO_X	SO_2	PM	VOC
695.5704	0.733169	2.788548	1.397407	1.735793	1.967023	6.33E-5

b) Compost shredding emissions

Same as AD because of similar amount of waste

c) RDF shredding emissions

MSW processed = 76.08 tonne/day

Electricity consumed by shredder = 7.46*76.08 = 567.55 kWh/day

Table 6: RDF shredding emissions /day

CO_2	CO	CH_4	NO_X	SO_2	PM	VOC
629.9805	0.664034	2.525598	1.265637	1.572114	1.781539	5.73E-05

d) Gasification shredding emissions

Same as RDF because of similar amount of waste

e) Incineration shredding emissions

Same as RDF because of similar amount of waste

10) Converting Emissions

a) AD converting emissions

Table 7: Emissions from biogas production [126].

kg/tonne	CO_2	CO	NO_X	SO_2	CH_4
Biogas production	15	0.011	0.046	0.0017	0.004

H_2S emissions are calculated considering 1% leakage of biogas during production

As per the method given in [127].

H_2S emissions = (Total biogas produced)*(volume % of H_2S in biogas)*(density of H_2S)*(% leakage)

55*0.0018*1.434*0.01 = 0.001419 kg/tonne

Biogas Engine emissions are calculated from [128]

Energy generated = 3.6 (electricity energy content)*110(electricity generated/tonne) = 396 MJ/tonne = 0.396 GJ/tonne

NO_X = 202 g/GJ = 202*0.396 = 79.992 g/tonne = 0.07999 kg/tonne

Similarly

VOC = 10 g/GJ = 0.00396 kg/tonne

CH_4 = 434 g/GJ = 0.1778 kg/tonne

CO = 310 g/GJ = 0.1267 kg/tonne

MSW processed = 84 tonne/day

Table 8: AD converting emission kg/day

Emissions (kg/day)	Total (biogas production+ biogas powered engine)
CO_2	1260
CO	11.5668
NO_X	45.3592
SO_2	0.1428
CH_4	15.2712
H_2S	0.1192
VOC	0.33264

Emissions to water [61]

Total N = 0.00003 kg/kWh = 0.00003/110 = 0.00000027 kg/tonne

COD = 0.0003 kg/kWh = 0.0003/110 = 0.0000027 kg/tonne

BOD = 0.000076 kg/kWh = 0.000076/110 = 0.00000069 kg/tonne

Table 9: AD converting water emissions kg/day

Total N	COD	BOD
0.00002268	0.000227	5.8E-05

b) Compost converting emissions

The calculations of emissions from composting are according to the balance of carbon and nitrogen. It has been assumed that 70% of total carbon is released into the air. The CO_2 and CH_4 emissions were calculated as 95% and 1.1% of the carbon released into air. Also, 68% of nitrogen is released into the air in the form of N_2, N_2O and NH_3. The total N is assumed to be released 3% [58].

As per composition of waste MSW in present case contains

Carbon = 282 kg/tonne (by dry weight)

Nitrogen = 1.16 kg/tonne (by dry weight)

C lost = 77% = CO_2 95% + 1.1% CH_4

CO_2 = (282*0.77)*0.95 = 206.28 kg/tonne

CH_4 = (282*0.77)*1.1 = 2.388 kg/tonne

Total N = (1.16*0.68)*0.03 = 0.02366 kg/tonne

From [134]

CO = 0.000149 kg/tonne

H_2S = 0.000404 kg/tonne

SO_2 = 0.07765 kg/tonne

NO_X = 0.0429 kg/tonne

HCL = 0.0129 kg/tonne

VOC = 0.0000318 kg/tonne

MSW processed = 84 tonne/day

Table 10: Compost converting emissions kg/day

CO_2	17327.52
CH_4	200.592
Total N	1.98744
CO	0.012516
H_2S	0.033936
SO_2	6.52
NO_X	3.6036
HCL	1.0836
VOC	0.0026712

Emissions to water

COD = 0.00014 kg/tonne [51]

Total N = 0.00155 kg/tonne [58]

c) RDF converting emissions

As per the table B2 of [141] the electricity and diesel consumption for making RDF from MSW is

Electricity = 64.3 kWh/tonne of RDF

Diesel = 10 litre/tonne of RDF

RDF produced = 43.89 tonne/day

Electricity consumed = 64.3*43.89 = 2822.12 kWh/day

Diesel consumed = 43.89*10 = 438.9 litre/day

Emission from diesel [100]

CO_2 = 3.18 kg/litre

CO = 1000 kg/Tj = (1000*1000)/ (1000000000) = 0.001 gram/kj = 0.001*44800 = 44.8 gram/litre = 0.0448 kg/litre

CH_4 = 5 kg/Tj = (5*1000)/ (1000000000) = 0.000005 gram/kj = 0.00005*44800 = 2.24 gram/litre = 0.00224 kg/litre

NO_X = 800 kg/Tj = (800*1000)/ (1000000000) = 0.0008 gram/kj = 0.0008*44800 = 35.84 gram/litre = 0.03584 kg/litre

VOC = 200 kg/Tj = (200*1000)/ (1000000000) = 0.0002 gram/kj = 0.0002*44800 = 8.96 gram/litre = 0.00896 kg/litre

As reported in [100] SO2 emission are calculated taking mileage 4 km/litre

SO_2 = 1.42 g/km = 1.42/4 = 0.000355 kg/litre

Emissions from electricity[101]

CO_2 = 1.11kg/kwh

CO = 0.00117 kg/kwh

CH_4 = 0.00445 kg/kwh

NO_X = 0.00223 kg/kwh

SO_2 = 0.00277 kg/kwh

VOC = 0.000000101 kg/kwh

Table 11: RDF converting emissions

Emissions (kg/day)	Diesel	Electricity	Total
CO_2	1395.7	3132.55	4528.26
CO	0.5596	3.30188	3.86148
CH_4	0.98314	12.5584	13.5416
NO_X	15.7302	6.29333	22.0235
SO_2	0.15581	7.81727	7.97308
VOC	3.93254	0.00029	3.93283

d) Gasification converting emissions

CO_2 is calculated as the composition of waste given to gasification plant calculated by tier 1 methodology = 922.3484 kg/tonne. Other emission are taken from [149]

Table 12: Gasification converting emissions kg/tonne

SO_2	0.052
HCL	0.032
NO_X	0.78
HF	0.00034
VOC	0.011
CO	0.1

MSW processed = 76.08 tonne/day

Table 13: Gasification converting emissions kg/day

SO_2	3.95616
HCL	2.43456
NO_X	59.3424
CO_2	70172
HF	0.0258672
VOC	0.83688
CO	7.608

e) Incineration converting emissions

CO_2 emissions are considered same as gasification because of same carbon content of MSW.

Table 14: Incineration converting emissions kg/tonne as per (US EPA)

SO_2	0.327
HCL	0.079
NO_X	1.24
CO	0.383

Table 15: Incineration converting emissions kg/tonne [149]

HF	0.001
CH_4	0.088
VOC	0.008

MSW processed = 76.08 tonne/day

Table 16: Incineration converting emissions kg/day

CO_2	70171.62
SO_2	24.87816
HCL	6.01032
NO_X	94.3392
CO	29.13864
HF	0.07608
VOC	0.60864
CH_4	6.69504

11) Residue Landfill Emissions

Landfill emissions including transportation per tonne of MSW are calculated in section 12 and presented in table 23 of section 12

Amount of residue for alternative techniques

AD, residue to land fill = 240 – 84 = 156 tonne/day

Compost, residue to land fill = 240 – 84 = 156 tonne/day

RDF, residue to land fill = 240 – 76.08 = 163.92 tonne

Gasification, residue to land fill = 240 – 76.08 = 163.92 tonne (excluding waste/ash)

Incineration, residue to land fill = 240 – 76.08 = 163.92 tonne (excluding waste/ash)

Table 17: Residue landfill emissions kg/day

Emissions kg/day	AD & Compost	RDF	Gasification	Incineration
CO_2	20025.304	21041.97328	23927.67	22015
CO	3.0888	3.245616	3.69072	3.3957
NO_X	109.356	114.90792	130.6664	120.2215
SO_2	9.0064	9.463648	10.76149	9.901267
CH_4	7215.0468	7581.349176	8621.056	7931.92
H_2S	0	0	0	0
VOC	9.984	10.49088	11.9296	10.976
Total N	0	0	0	0
HCL	0.468	0.49176	0.5592	0.5145
HF	0.468	0.49176	0.5592	0.5145
H_2S	17.16	17.93	17.93	17.93

Table 18: Residue landfill emissions to water kg/day

COD	0.26676	0.2803	0.318744	0.293265
BOD	0.151944	0.15965	0.1815536	0.167041
Total N	1.4664	1.54084	1.75216	1.6121
Phosphorus	0.011856	0.012457	0.0141664	0.013034

12) Avoided Emissions

a) Landfill emissions

The emissions of methane and carbon from landfill are estimated using Landgem model version 3.02 for the MSW taken for this study. The value of methane generation potential L_o is taken 70.2 m^3/tonne and “k” that is methane generation rate is taken as 0.032/year. The emission factors for a unit tonne of MSW are calculated from the total landfill emissions and total MSW disposed to landfill (240 tpd of MSW for 20 years) (including emissions upto 100 years after landfill closure).

Estimated CO_2 emissions per tonne of MSW = 221971.4/1752000 = 126.66 kg

Estimated CH_4 emissions per tonne of MSW = 80577.91/1752000 = 46.25 kg

Table 19: Landfill emissions kg/tonne (Zaman, 2010; Smith et al., 2015;Yay, 2015)

SO_2	0.053
HCL	0.003
NO_X	0.68
HF	0.003
VOC	0.064
CO	0.0078
H_2S	0.11

Table 20: Landfill emissions kg/day

CO_2	30398.4
CH_4	11100
CO	1.872
SO_2	12.72
HCL	0.72
NO_X	163.2
HF	0.72
VOC	15.36
H_2S	26.4

Emissions to water

Total N = 9.4 g/tonne [149]

Phosphorus = 0.076 g/tonne [149]

COD = 1.71g/tonne [109]

BOD = 0.974 g/tonne [109]

Table 21: Landfill emissions to water kg/day

COD	0.4104
BOD	0.23376
Total N	2.256
Phosphorus	0.01824

b) Transport emissions

Taking emission factors for transport as presented in table 1 of section 8.

Waste to handle = 240 tonne/day

Distance for one round trip to landfill = 40 km

Trips required = 240/12 = 20 trips/day

Total km to travel = 40*20 = 800 km/day

Table 22: Transport emissions to kg/day

CO_2	CH_4	CO	NO_X	SO_2
409.76	0.072	2.88	5.04	1.136

Table 23: Total avoided air emissions

	Landfill kg/day	Transport kg/day	Total kg/day	Total kg/tonne
CO_2	30398.4	409.76	30808.16	128.3673333
CO	1.872	2.88	4.752	0.0198
NO_X	163.2	5.04	168.24	0.701
SO_2	12.72	1.136	13.856	0.057733333
CH_4	11100	0.072	11100.072	46.2503
VOC	15.36		15.36	0.064
HCL	0.72		0.72	0.003
HF	0.72		0.72	0.003

Table 24: Total avoided emissions to water

Emissions to Water	kg/day	kg/tonne
COD	0.4104	0.00171
BOD	0.23376	0.000974
Total N	2.256	0.0094
Phosphorus	0.01824	0.000076

c) Coal based electricity emissions

Table 25: Coal based electricity emissions [102]

kg/kWh	CO_2	CH_4	CO	NO_X	SO_2
	1.21	0.03	0.009	0.005	0.0075

Electricity produced by AD, incineration and gasification is 9.24 MWh/day, 12.7 MWh/day and 18.25 MWh/day.

Table 26: AD electricity avoided emissions kg/day

CO_2	CO	NO_X	SO_2	CH_4
11180.4	83.16	46.2	69.3	277.2

Table 27: Incineration electricity avoided emissions kg/day

CO_2	CO	NO_X	SO_2	CH_4
15367	114.3	63.5	95.25	381

Table 28: Gasification electricity avoided emissions kg/day

CO_2	CO	NO_X	SO_2	CH_4
22082.5	164.25	91.25	136.875	547.5

d) Emissions from fertilizer use

Contents of compost from segregated waste [133]

Total N (% dm) = 1.06 = 10.6 kg/tonne

Total P (% dm) = 0.27 = 2.7 kg/tonne

Total K (% dm) = 0.55 = 5.5 kg/tonne

Emissions from fertilizers [103]

Nitrogen = 1.35 kg CO_2 eq. /kg

Phosphorus = 0.2 kg CO_2 eq. /kg

Potassium = 0.15 kg CO_2 eq. /kg

One tonne of compost replaces

Total N = 10.6 kg = 14.31 kg CO_2 eq.

Total P = 2.7 kg = 0.54 kg CO_2 eq.

Total K = 5.5 kg = 0.825 kg CO_2 eq.

In our case compost produced per day is 28 tonne

Then avoided emissions/day

Nitrogen = 400.68 kg CO_2 eq./day

Phosphorus = 15.12 kg CO_2 eq./day

Potassium = 23.1 kg CO_2 eq./day

Total = 438.84 kg CO_2 eq./day

For AD plant compost produced = 6.9 tpd

Then avoided emissions/day

Nitrogen = 78.73 kg CO_2 eq./day

Phosphorus = 3.72 kg CO_2 eq./day

Potassium = 5.69 kg CO_2 eq./day

Total = 88.14 kg CO_2 eq./day

e) Emissions from use of coal in cement plants

Considering the calorific value of RDF 12.9 Gj/tonne and coal 23Gj/tonne

One tonne of RDF can replace 560 kg of coal. The emissions related combustion of coal and RDF in cement kilns are given in Table 29.

Table 29: Emissions for cement kilns from use of coal and RDF [142]

Emissions	Coal kg/560kg	RDF kg/tonne
CO_2	3998.33	1020.10
NO_X	7.35	1.10
SO_2	1.01	1.24
CH_4	7.53	1.60
VOC	0.061	0.0496
HCL	0.020	0.0365
HF	0.0025	0.008

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Appendix B

Supplementary Material to **Chapter 2, Section 2.4**, “Evaluation of rice straw processing technologies”.

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(1) Economic parameters of rice straw processing technologies

(a) Incineration

A 12 MW rice straw based power plant in village Ghanour district Patiala (Punjab) is visited and found that consuming 400 tonnes/day of feedstock at 90% capacity factor the electricity produced is 648 kWh/tonne. After 12% internal consumption 570 kWh/tonne power is available for the grid.

Cost = 6.1 crore/MW [158] = 73.2 crore for 12 MW

Assuming investment was spread over 20 years and 365 days per year gives an average of INR 100027.39/day
Capital cost = 100027.39/400 = 250.06 INR/tonne
Operating and maintenance cost = 4726000 INR/year for 1 MW = 56712000/year for 12 MW

56712000/365 = 155375.34 INR/day = 155375.34/400 = 388.43 INR/tonne

Cost of feedstock = 3342.60 INR/tonne

Total cost = 3981.09

Tariff rate 7.88/kwh (as provided by Central Electricity Regulatory Commission, Government of India)

Product value = 7.88*570 = 4491.6 INR/tonne

Economic benefits = 510.51 INR/tonne

(b) Gasification

The operational experience of a gasification plant working with feedstock having calorific value 15 MJ/kg reported an efficiency of 18% [159]. The calorific value of rice straw is 14 MJ/kg [182].

The power potential of rice straw with 18% efficiency = 14*1000*0.18 = 2520 MJ/tonne = 2520/3.6 = 700 kwh/tonne

Straw processing capacity for1 MW plant = 24000/777 = 30 tonne/day

Capital cost 592.859 lakh/MW after subsidy 442.859 lakh/MW [158]

Operating and maintaince cost = 49.97 lakh/year

Assuming investment was spread over 20 years and 365 days per year gives an average of INR 6066.56/day

Capital cost = 6066.56/30 = 202.21 INR/tonne
Operating and maintaince cost = 4997000 INR/year = 4997000/365 = 13690.41/30 = 456.34 INR/tonne

Cost of feedstock = 3342.60 INR/tonne

Total cost = 4001.15 INR /tonne

After 10% internal consumption 630 kwh/tonne is available for grid

Tariff = 7.20/kwh [158]

Product value = 4536 INR/tonne

Economic benefits = 534.85 INR/tonne

(c) AD

Operational experience of 1 MW rice straw based biogas power plant reported [163] and found that from 10 tonne of straw 3000 m^3/day biogas is generated which further generate 6000 kwh/day of electricity. That shows the power potential of 600 kwh/tonne. By processing 8750 tonne/year it produces 439 tonne of manure that is 5% of the total feedstock processed [186].

Plant cost = 11.85764 crore/MW [158] After subsidy = 885.764 lakh/MW

Capacity 40 tonne/day [163]

Assuming investment was spread over 20 years and 365 days per year gives an average of INR 12133.75/day
Capital cost = 12133.75/40 = 303.34 INR/tonne
Operating and maintaince cost = 4997000 INR/year = 4997000/365 = 13690.41/40 = 342.26 INR/tonne

Cost of feedstock = 3342.60 INR/tonne

Total cost = 3988.2 INR/tonne

Electricity produced = 600 kwh/tonne

After 8% internal consumption 552 kwh/tonne

Tariff rate 7.42/kwh [158]

Product value from electricity = 7.42*552 = 4095.84 INR/tonne

Compost produced = 1000*0.05 = 50 kg/tonne

Product value from compost = 50*1.200 = 60 INR/tonne

Total product value = 4095.84+60 = 4155.84 INR/tonne

Economic benefits = 167.64 INR/tonne

(d) Fermentation

Cost 35 crore, capacity 10 tonne/day, ethanol production 300 litre/tonne for mix agricultural wastes like rice, wheat and sugarcane straws respectively [169].

Yield of rice straw is = 260 litre/tonne [82]

Assuming investment was spread over 15 years and 365 days per year gives an average of INR 63926.94/day

Ethanol produced = 3000 litre/day

Cost of ethanol per litre = 63926.94/3000 = 21.30 INR

Feedstock cost 3342.60 including collection, transport and storage charges [158]

Capital cost	= 21.30 INR/litre
Recovery of ethanol	= 260 litre/tonne
Capital cost	= 5538 INR/tonne
Cost of feedstock	= 3342.60 INR/tonne

Operating and maintenance cost [187]

Steam cost @ Rice Husk or Bagasse at Rs. 2,000/tonne	= 1.00 INR/litre
Power cost @ Rs. 4.5/kWh	= 0.59 INR/litre
Chemical cost	= 0.2 INR/litre
Labour cost	= 0.38 INR/litre
Repair and Maintenance costs	= 0.15 INR/litre
Cost of Replacement of Molecular Sieve	= 0.02 INR/litre
Total	= 2.34 INR/litre
Maintenance cost	= 608.4 INR/tonne

Total cost = 3342.60+5538+608.4 = 9490 INR/tonne

Price of ethanol = 39 INR/L

Income = 39*260 = 10140 INR/tonne

The each litre of ethanol production provides 5-10 litres of stillage with 0.8 kg of total solids [173]. With ethanol yields of 260 L/tonne of straw [82] the stillage in terms of total solids = 0.8*260 = 208 kg/tonne of straw

Compost produced 208 kg/tonne

Income = 208*1.200 = 249.6 INR/tonne

Total income = 10389.6 INR/tonne

Economic benefits = 899.6 INR/tonne

(e) Combined operation

The heat and electricity cost are not applicable here, because heat and electricity demand of the plant will be supplied by AD.

Capital cost of fermentation (as calculated in section d)	= 5538 INR/tonne
Cost of feedstock	= 3342.60 INR/tonne
Recovery of ethanol	= 260 litre/tonne

Operating and maintenance cost [187]

Chemical cost	= 0.2 INR/litre
Labour cost	= 0.38 INR/litre
Repair and Maintenance costs	= 0.15 INR/litre
Cost of Replacement of Molecular Sieve	= 0.02 INR/litre
Total	= 0.75 INR/litre
Operating and maintenance cost	= 195 INR/tonne

Total cost = 3342.60+5538+195 = 9075.6 INR/tonne

Income = 39*260 = 10140 INR/tonne

The each litre of ethanol production provides 5-10 litres of stillage with 0.8 kg of total solids [173]. The specific excess electricity yield of stillage = 0.37 kwh/L of ethanol [82].

With ethanol yields of 260 L/tonne of straw [82], the stillage in terms of total solids = 0.8*260 = 208 kg/tonne of straw

From section (c)

Capital cost for AD plant = 12133.75/40 = 303.34 INR/tonne = 0.30334 INR/kg = 0.30334*208 = 63.09 INR/tonne of straw

Operating and maintaince cost for AD plant = 342.26 INR/tonne = 0.34226 INR/kg = 0.34226*208 = 71.19 INR//tonne of straw

Total cost = 645.6 INR/tonne of feedstock (excluding feedstock cost because stillage is available free within the plant)

Total processing cost for AD = 63.09+71.19 = 134.28 INR/tonne of straw

Electricity to grid = 0.37*260 = 96.2 kWh/tonne of straw

Tariff rate 6.06 INR/kwh (as per tariff rate provided for co-generation projects) [158]

Income = 96.2*6.06 = 582.97 INR/tonne of straw

Capital cost of integrated operation = 5538+63.09 = 5601.09 = INR/tonne

Operating and maintenance cost of integrated operation = 195+71.19 = 266.19 INR/tonne

Total cost for integrated operation = 3342.60+5601.09+266.19 = 9209.88 INR/tonne

Total income from integrated operation = 10140 + 582.97 = 10722.97 INR/tonne

Economic benefits = 151.09 INR/tonne

Composed produced = 208*0.05 = 10.4 kg/tonne

Product value from compost = 10.4*1.200 = 12.48 INR/tonne of straw

Total economic benefit = 1513.09+12.48 = 1525.57 INR/tonne of straw

(2) Environmental parameters of rice straw processing technologies

(a) Emissions from straw preparation

Straw chopping consumes 4.5 litres of diesel for one acre

Straw baling consumes 3 litres for one acre

Transportation by tractor-trolley consumes 5 litres for 20 km in loaded and unloaded conditions

That shows the mileage of 4 km/litre

Capacity of trolley = 5.5 tonne

Straw yield = 24 quintals/acre (if processed day time)

= 26 quintals/acre (if processed night time)

Considering straw yield 2.4 tonne/acre

Processing of one tonne of straw consumes diesel

(a) Chopping = 4.5/2.4 = 1.87 litre/tonne
(b) Balling = 3/2.4 = 1.25 litre/tonne
(c) Transportation for 40 km = 40/4 = 10 litre/5.5 tonne = 1.81 litre/tonne

Table 2: Emissions by tractors [100]

Emissions (gm/km)	CO_2	CO	NO_X	SO_2	CH_4	PM
	515.2	5.1	1.28	1.42	0.09	0.2

Table 3: Emissions gm/litre taking mileage on road 4 km/litre

Emissions (gm/litre)	CO_2	CO	NO_X	SO_2	CH_4	PM
	128.8	1.27	0.32	0.35	0.02	0.05

Table 4: Emissions from the processing of one tonne of rice straw

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	CH_4	PM
Straw chopping	0.24085	0.00237	0.00059	0.00065	0.00003	0.00009
Straw Baling	0.161	0.00158	0.0004	0.00043	0.00002	0.00006
Transportation	0.23312	0.00229	0.00057	0.00063	0.0000362	0.00009
Total	0.63498	0.00626	0.00157	0.00172	0.00009	0.00024

(b) Emissions from incineration

Table 5: Emissions from rice straw-fired boiler [84]

Emissions (kg/kWh)	CO_2	CO	NO_X	SO_2	CH_4
	0.36	0.0009	0.0007	0.00004	0.0003

Table 6: Emissions from rice straw-fired boiler taking electricity potential of 648 kWh/tonne

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	CH_4
	233.28	0.5832	0.4536	0.02592	0.1944

(c) Emissions from gasification

Power potential of rice straw gasification = 777 kwh/tonne

CO_2 = 233.28 kg/tonne same as incineration due to same carbon content

From [160]

CO = 0.86 kg/GWh = (0.86/1000000)*777 = 0.00066 kg/tonne

Similarly

VOC = 515 = 0.4001kg/tonne

PM = 3.7 kg/GWh = 0.00287 kg/tonne

From [161]

NO_X = 0.7 g/kWh = (0.7*777)/1000 = 0.54 kg/tonne

The calorific value of rice straw is 15.54 MJ/kg = 15.54 GJ/tonne [162].

SO_2 = 0.0008 kg/GJ of biomass (agricultural residue) = 0.00008*15.54 = 0.01243 kg/tonne

Similarly

CH_4 = 0.000037 kg/GJ = 0.0574 kg/tonne

Table 7: Emissions from gasification

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	VOC	CH_4	PM
	233.28	0.00066	0.54	0.01243	0.4001	0.0574	0.00287

(d) Emissions from AD

Emissions from biogas are calculated considering 1% leakage of biogas during production as per the method is given in [127]. 10 tonne of straw produces 3000 m^3/day that shows the biogas yield of straw 300 m3/tonne [163].

CH_4 emissions = (Total biogas produced)*(volume % of CH_4 in biogas)*(density of CH_4)*(% leakage)

= 300*0.60*0.717*0.01 = 0.12906 kg/tonne

CO_2 emissions = (Total biogas produced)*(volume % of CO_2 in biogas)*(density of CO_2)*(% leakage)

= 300*0.345*1.977*0.01 = 2.0461 kg/tonne

H_2S emissions = (Total biogas produced)*(volume % of H_2S in biogas)*(density of H_2S)*(% leakage)

= 300*0.0018*1.434*0.01 = 0.0077436 kg/tonne

Biogas Engine emissions are calculated from [128]

Energy generated = 3.6 (electricity energy content)*600 (electricity generated/tonne) = 2160 MJ/tonne = 2.16 GJ/tonne

NO_X = 202 g/GJ = 202*2.16 = 436.32 g/tonne = 0.04363 kg/tonne

Similarly

VOC = 10 g/GJ = 0.0216 kg/tonne

CH_4 = 434 g/GJ = 0.9374 kg/tonne

CO = 310 g/GJ = 0.6696 kg/tonne

Table 8: Emissions from AD

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	CH_4	H_2S
Biogas Production	2.0461	0.0	0.0	0.00004	0.12906	0.0077436
Biogas Powered Engines	0.0	0.6696	0.04363	0.0	0.9374	0.0
Total	2.0461	0.6696	0.04363	0.00004	1.06646	0.007744

(e) Emissions from fermentation

Energy content of ethanol = 21.2 MJ/L [78]

Ethanol yield of rice straw = 260 L/tonne

CO_2 = 0.0125 kg/MJ = 0.0125*21.2 = 0.265 kg/L of ethanol = 0.265*260 = 68.9 kg/tonne of straw

Similarly

CO = 0.00004 kg/MJ = 0.22048 kg/tonne

NO_X = 0.0000205 kg/MJ = 0.1129 kg/tonne

SO2 = 0.0000549 kg/MJ = 0.3026 kg/tonne

CH_4 = 0.0000002393 kg/MJ = 0.001319 kg/tonne

PM = 0.0000009482 kg/MJ = 0.005226 kg/tonne

Table 9: Emissions from fermentation

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	CH_4	PM
Ethanol Production	68.9	0.22048	0.1129	0.3026	0.001319	0.005226

Emissions to water

COD = 48 kg/1000L ethanol = (48/1000)*260 = 12.48 kg/tonne straw

Nitrate = 0.38 kg/1000L ethanol = (0.38/1000)*260 = 0.0988/tonne straw

(f) Emission from Combined operation

In section (d) emissions are calculated for 552 kWh of power generation by AD. By calculating the emissions per unit of power the total emissions are calculated for 96.2 kWh of power that is generated by cogeneration plant. The emissions from fermentation will remain the same as presented in section (e).

Table 10: Emissions from combined operation

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	VOC	CH_4	H_2S	PM
AD	0.3565	0.1166	0.0076	0.0000069	0.0037	0.1858	0.0013	--
Fermentation	68.9	0.2204	0.1129	0.3026	--	0.00131	--	0.0052
Total	69.25	0.3371	0.1205	0.3026	0.0037	0.1871	0.00135	0.00522

(g) Avoided Emissions

Table 11: Emissions from open field burning [153]

Emissions (kg/tonne)	CO_2	CO	NO_X	SO_2	CH_4	PM
	1460	34.70	3.1	2	1.2	13

Table 12: Coal based electricity emissions [83]

kg/kWh	CO_2	CH_4	CO	NO_X	SO_2	PM
	1.21	0.03	0.009	0.005	0.0075	0.002

Table 13: Emissions from the production of fertilizers [156]

kg/kg fertilizer	GWP kg CO_2 eq.	AP kg SO_2 eq.	EP kg PO_4 eq.
Nitrogen	6.8	0.0417	0.0219
Phosphorus	1.2	0.0456	0.0326
Potassium	0.5	0.00245	0.00121

Table 14: Contents of rice straw [156]

kg/kg straw	Nitrogen	Phosphorus	Potassium
	0.0062	0.0014	0.00194

Composed produced by AD = 50 kg/tonne

Nitrogen = 50*0.0062 = 0.31 kg/tonne

Phosphorus = 50*0.0014 = 0.07 kg/tonne

Potassium = 50*0.00194 = 0.097 kg/tonne

Table 15: Avoided emissions for AD

kg/tonne	GWP kg CO_2 eq.	AP kg SO_2 eq.	EP kg PO_4 eq.
Nitrogen	0.31 *6.8 = 2.1	0.31 *0.0417 = 0.0129	0.31 *0.0219 = 0.00678
Phosphorus	0.07*1.2 = 0.084	0.07*0.0456 = 0.0031	0.07*0.0326 = 0.002282
Potassium	0.097*0.5 = 0.0485	0.097*0.00245 = 0.00023	0.097*0.00121 = 0.00011
Total	2.2325	0.01623	0.009172

Composed produced by combined operation = 10.4 kg/tonne

Nitrogen = 10.4*0.0062 = 0.0624 kg/tonne

Phosphorus = 10.4*0.0014 = 0.01456 kg/tonne

Potassium = 10.4*0.00194 = 0.02017 kg/tonne

Table 16: Avoided emissions for combined operation

kg/tonne	GWP kg CO_2 eq.	AP kg SO_2 eq.	EP kg PO_4 eq.
Nitrogen	0.0624*6.8 = 0.4243	0.0624*0.0417 = 0.0026	0.0624*0.0219 = 0.00136
Phosphorus	0.01456*1.2 = 0.0174	0.01456*0.0456 = 0.00066	0.01456*0.0326 = 0.00047
Potassium	0.02017*0.5 = 0.01008	0.02017*0.00245 = 0.000049	0.02017*0.00121 = 0.000024
Total	-1060.07955	0.003309	0.001854

Compost produced by fermentation 208 kg/tonne

Nitrogen = 208*0.0062 = 1.28 kg/tonne

Phosphorus = 208*0.0014 = 0.2912 kg/tonne

Potassium = 208*0.00194 = 0.4035 kg/tonne

Table 17: Avoided emissions for fermentation

kg/tonne	GWP kg CO_2 eq.	AP kg SO_2 eq.	EP kg PO_4 eq.
Nitrogen	1.28 *6.8 = 8.7	1.28 *0.0417 = 0.0533	1.28 *0.0219 = 0.028
Phosphorus	0.2912 *1.2 = 0.349	0.2912 *0.0456 = 0.0132	0.2912 *0.0326 = 0.0094
Potassium	0.4035 *0.5 = 0.2017	0.4035 *0.00245 = 0.00098	0.4035 *0.00121 = 0.00048
Total	-878.59955	0.06748	0.03788

Bioethanol production potential of rice straw is 260 L/tonne that can replace 170 L of gasoline (based on LHV of ethanol and gasoline about 21.2 and 32.4 MJ/L, respectively).

Table 18: Estimated emission factors for passenger cars using E-15 (15% ethanol mix with gasoline) and 100% gasoline [154]

(g/MJ)	CO_2	CH_4	NO_X	CO	VOC
E-15	69.7	0.01	0.19	1.19	0.25
Gasoline	73	0.02	0.6	13	1.5

Table 19: Estimated emission factors for passenger cars using E-15 (15% ethanol mix with gasoline) and 100% gasoline

(kg/tonne)	CO_2	CH_4	NO_X	CO	VOC
E-15	384.1864	0.05512	1.04728	6.55928	1.378
Gasoline	402.084	0.11016	3.3048	71.604	8.262

Table 20: Estimated emission factors Gasoline production [155]

	CO_2	CO	NO_X	SO_2	VOC
mg/MJ	6000	0.63	16	6.5	190
kg/tonne	35.088	0.003684	0.093568	0.038012	1.11112

References

[1] M. Herrando and C. N. Markides, "Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK : Techno-economic considerations," *Appl. Energy*, vol. 161, pp. 512–532, 2016.

[2] A. Banerji, "Microgrid: A review," *c2013 IEEE Glob. Humanit. Technol. Conf. South Asia Satell. GHTC-SAS 2013*, pp. 27–35, 2013.

[3] T. Lee, K. Ha, H. Yoo, J. Seo, and M. Shin, "Research for Data acquisition equipment with micro-Grid system," *Proc. ICECE 2008 - 5th Int. Conf. Electr. Comput. Eng.*, December, p. 20–22, 2008.

[4] A. K. Akella, R. P. Saini, and M. P. Sharma, "Social , economical and environmental impacts of renewable energy systems," *Renew. Energy*, vol. 34, p. 390–396, 2009.

[5] W. Science, D. J. Batstone, and I. Angelidaki, "Anaerobic digestion model No 1 (ADM1) The IWA Anaerobic Digestion Model No 1 (ADM1)," *Water Sci. Technol.*, vol. 1, 2002.

[6] M. A. Rosen, A. Moharamian, S. Soltani, M. A. Rosen, and S. M. S. Mahmoudi, "A comparative thermoeconomic evaluation of three biomass and biomass- natural gas fired combined cycles using organic Rankine cycles A comparative thermoeconomic evaluation of three biomass and biomass-natural gas fi red combined cycles using organic Rankine cycles," *J. Clean. Prod.*, vol. 161, June, p. 524–544, 2017.

[7] R. Basumatary, P. Dutta, M. Prasad, and K. Srinivasan, "Thermal modeling of activated carbon based adsorptive natural gas storage system," vol. 43, pp. 541–549, 2005.

[8] C. Hachem-vermette and K. S. Grewal, "Investigation of the impact of residential mixture on energy and environmental performance of mixed use neighborhoods," *Appl. Energy*, vol. 241, March, p. 362–379, 2019.

[9] M. Wall, M. Snow, J. Dahlberg, M. Lundgren, and C. Lindkvist, "Urban Planning for Solar Energy - IEA SHC Task 51," in *ISES Solar World Congress 2017*, 2017, January.

[10] S. V. Shaili Vyas, Priya Prajapati, Anil V. Shah, "Municipal solid waste management: Dynamics, risk assessment, ecological influence, advancements, constraints and perspectives," *Sci. Total Environ.*, vol. 814, p. 152802, 2022.

[11] S. Xiao and H. Dong, "An overview of the municipal solid waste management modes and innovations in Shanghai , China," vol. 2017, 2020.

[12] R. R. Viet, C. Gurukula, K. Vishwavidyalaya, and A. K. Chopra, "Scenario of solid waste management in present Indian context," *Casp. J. Environ. Sci. Scenar.*, vol. 7, pp. 45–53, 2014.

[13] D. Majumdar, A. Srivastava, D. Majumdar, and A. Srivastava, "Volatile organic compound emissions from municipal solid waste disposal sites : A case study of Mumbai , India Volatile organic compound emissions from municipal solid waste disposal sites : A case study of Mumbai , India," vol. 2247, 2012.

[14] A. Singh and P. Basak, "The present energy scenario and need of microgrid in India," in *Frontiers in Computer, Communication and Electrical Engineering* –, 2016, May, p. 313–317.

[15] M. I. Shamshad Khan, Raheel Anjum, Syed Turab Raza, Nazir Ahmed Bazai, "Technologies for municipal solid waste management: Current status, challenges, and future perspectives," *Chemosphere*, vol. 288, p. 132403, 2022.

[16] H. Khandelwal, H. Dhar, A. K. Thalla, and S. Kumar, "Application of Life Cycle Assessment in Municipal Solid Waste Management : A Worldwide Critical Review," *J. Clean. Prod.*, 2018.

[17] S. A. Edrisi and P. C. Abhilash, "Exploring marginal and degraded lands for biomass and bioenergy production : An Indian scenario," *Renew. Sustain. Energy Rev.*, vol. 54, p. 1537–1551, 2016.

[18] FAO, "Food and Agriculture Organization, United Nations. http://faostat.fao.org/ (accessed February 04, 2018)," 2017.

[19] K. Hassan, R. Chowdhury, S. Ghosh, D. Manna, A. Pappinen, and S. Kuittinen, "Energy and environmental impact assessment of Indian rice straw for the production of second-generation bioethanol," *Sustain. Energy Technol. Assessments*, vol. 47, August, p. 101546, 2021.

[20] D. Cardoen, P. Joshi, L. Diels, P. M. Sarma, and D. Pant, "Agriculture biomass in India : Part 1 . Estimation and characterization," *"Resources, Conserv. Recycl.*, vol. 102, p. 39–48, 2015.

[21] CEA, "Growth of electricity sector in India from 1947 to 2013. Central electricity authority Goverenment of India. http://www.indiaenvironmentportal.org.in/files/file/growth of electricity sector in india.pdf (accessed 25 January 2018)," 2013.

[22] J. Singh, "Overview of electric power potential of surplus agricultural biomass from economic, social, environmental and technical perspective - A case study of Punjab," *Renew. Sustain. Energy Rev.*, vol. 42, p. 286–297, 2015.

[23] M. Amann *et al.*, "Managing future air quality in megacities: A case study for Delhi," *Atmos. Environ.*, 2017.

[24] A. Sharma, G. Singh, and S. Kumar, "Biofuel from rice straw," *J. Clean. Prod.*, vol. 277, p. 124101, 2020.

[25] C. Sarkar *et al.*, "How the Atmosphere over Eastern Himalaya , India is Polluted with Carbonyl Compounds ? Temporal Variability and Identification of Sources," *Aerosol Air Qual. Res.*, p. 2206–2223, 2017.

[26] W. Harris, S. Member, M. Ehsani, and L. Fellow, "Socioeconomically Sustainable Rural Microgrid Engineering Desig". IEEE Global Humanitarian Technology Conference (GHTC)

2017.

[27] R. Amirante, S. Bruno, E. Distaso, M. La, and P. Tamburrano, "A biomass small-scale externally fired combined cycle plant for heat and power generation in rural

communities," *Reinf. Plast.*, vol. 28, p. 36–46, 2019.

[28] M. M. Samy, "A Hybrid PV-Biomass Generation Based Micro- Grid for the Irrigation System of a Major Land Reclamation Project in Kingdom of Saudi Arabia (KSA) - Case Study of Albaha Area," *2018 IEEE Int. Conf. Environ. Electr. Eng. 2018 IEEE Ind. Commer. Power Syst. Eur. (EEEIC / I&CPS Eur.*, pp. 1–8, 2018).

[29] A. Heydari and A. Askarzadeh, "Optimization of a biomass-based photovoltaic power plant for an off-grid application subject to loss of power supply probability concept," *Appl. Energy*, vol. 165, p. 601–611, 2016.

[30] S. You, H. Tong, J. Armin-hoiland, Y. Wah, and C. Wang, "Techno-economic and greenhouse gas savings assessment of decentralized biomass gasi fi cation for electrifying the rural areas of Indonesia," *Appl. Energy*, June, pp. 0–1, 2017.

[31] T. Patarau, D. Petreus, R. Etz, and E. Lazar, "Techno-economic feasibility study on an off-grid renewable energy microgrid for an isolated greenhouse in Romania," *2018 IEEE 18th Int. Power Electron. Motion Control Conf.*, p. 445–450, 2018.

[32] H. Li, X. Zhang, L. Liu, S. Wang, and G. Zhang, "Proposal and research on a combined heating and power system integrating biomass partial gasification with ground source heat pump," *Energy Convers. Manag.*, vol. 145, p. 158–168, 2017.

[33] Z. Gha, M. Mahmoudi, A. H. Mosa, and L. G. Farshi, "Thermoeconomic assessment of a novel integrated biomass based power generation system including gas turbine cycle , solid oxide fuel cell and Rankine cycle," vol. 161, November 2017, pp. 1–12, 2018.

[34] A. L. A. M. Jessé Luís Padilha, "Waste-to-energy effect in municipal solid waste treatment for small cities in Brazil," *Energy Convers. Manag.*, vol. 265, p. 115743, 2022.

[35] A. Husain *et al.*, "Evaluation of cost benefit analysis of municipal solid waste management systems," *J. King Saud Univ. - Sci.*, vol. 34, p. 101997, 2022.

[36] D. Roy, S. Samanta, and S. Ghosh, "Techno-economic and environmental analyses of a biomass based system employing solid oxide fuel cell, externally fired gas turbine and

organic Rankine cycle," *J. Clean. Prod.*, 2019.

[37] K. Li, J. Song, H. Duan, and S. Wang, "Integrated assessment of straw utilization for energy production from views of regional energy , environmental and socioeconomic bene fi ts," *J. Clean. Prod.*, vol. 190, p. 787–798, 2018.

[38] F. Diehlmann, T. Zimmer, S. Glöser-chahoud, and M. Wiens, "Techno-economic assessment of utilization pathways for rice straw: A simulation- optimization approach," *J. Clean. Prod.*, 2019.

[39] S. Dhundhara, Y. Pal, and A. Williams, "Techno-economic analysis of the lithium-ion and lead-acid battery in microgrid systems," *Energy Convers. Manag.*, vol. 177, May, p. 122–142, 2018.

[40] J. Ahmad *et al.*, "Techno economic analysis of a wind-photovoltaic-biomass hybrid renewable energy system for rural electrification: A case study of Kallar Kahar," *Energy*, 2018.

[41] M. Younas, R. Kamal, M. S. Khalid, and A. Qamar, "Economic Planning for Remote Community Microgrid Containing Solar PV , Biomass Gasifier and Microhydro," *2018 Clemson Univ. Power Syst. Conf.*, pp. 1–7, 2018.

[42] P. Arranz-piera, F. Kemausuor, L. Darkwah, and I. Edjekumhene, "Mini-grid electricity service based on local agricultural residues: Feasibility study in rural Ghana," *Energy*, 2018.

[43] A. Gojiya, D. Deb, and K. K. R. Iyer, "Feasibility study of power generation from agricultural residue in comparison with soil incorporation of residue," *Renew. Energy*, vol. 134, pp. 416–425, 2019.

[44] S. Mazzola, M. Astolfi, and E. Macchi, "The potential role of solid biomass for rural electrification : A techno economic analysis for a hybrid microgrid in India," *Appl. Energy*, vol. 169, pp. 370–383, 2016.

[45] I. Quispe, R. Navia, and R. Kahhat, "Life Cycle Assessment of rice husk as an energy

source . A Peruvian case study," *J. Clean. Prod.*, vol. 209, pp. 1235–1244, 2019.

[46] C. Y. Li, J. Y. Wu, C. Chavasint, S. Sampattagul, T. Kiatsiriroat, and R. Z. Wang, "Multi-criteria optimization for a biomass gasification-integrated combined cooling , heating , and power system based on life-cycle assessment," vol. 178, September, pp. 383–399, 2018.

[47] J. Mikhail, A. Gallego-schmid, and A. Azapagic, "Environmental sustainability of small-scale biomass power technologies for agricultural communities in developing countries," *Renew. Energy*, vol. 141, pp. 493–506, 2019.

[48] T. Sarkar, A. Bhattacharjee, H. Samanta, and K. Bhattacharya, "Optimal design and implementation of solar PV-wind-biogas-VRFB storage integrated smart hybrid microgrid for ensuring zero loss of power supply probability," *Energy Convers. Manag.*, vol. 191, January, pp. 102–118, 2019.

[49] C. M. Sastre *et al.*, "Centralised electricity production from winter cereals biomass grown under central-northern Spain conditions : Global warming and energy yield assessments," *Appl. Energy*, vol. 114, February 2011, pp. 737–748, 2020.

[50] M. Gear, J. Sadhukhan, R. Thorpe, R. Clift, and J. Seville, "A life cycle assessment data analysis toolkit for the design of novel processes – A case study for a thermal cracking process for mixed plastic waste," *J. Clean. Prod.*, 2018.

[51] Q. Song, Z. Wang, and J. Li, "Environmental performance of municipal solid waste strategies based on LCA method : a case study of Macau," *J. Clean. Prod.*, vol. 57, pp. 92–100, 2013.

[52] Y. Thakur and S. S. Katoch, "Emerging Technologies in Biomedical Waste Treatment and Disposal Emerging Technologies in Biomedical Waste Treatment and Disposal," January 2012, 2019.

[53] Y. Wang, Y. Yan, G. Chen, J. Zuo, B. Yan, and P. Yin, "Effectiveness of waste-to-energy approaches in China : from the perspective of greenhouse gas emission reduction," *J. Clean. Prod.*, pp. 1–7, 2015.

[54] I. Istrate, D. Iribarren, J. Gálvez-martos, and J. Dufour, "Resources , Conservation & Recycling Review of life-cycle environmental consequences of waste-to-energy solutions on the municipal solid waste management system," *Resour. Conserv. Recycl.*, vol. 157, October 2019, p. 104778, 2020.

[55] C. Mukherjee, J. Denney, E. G. Mbonimpa, J. Slagley, and R. Bhowmik, "A review on municipal solid waste-to-energy trends in the USA," *Renew. Sustain. Energy Rev.*, vol. 119, October 2019, p. 109512, 2020.

[56] T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, "Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria," *Appl. Energy*, vol. 201, pp. 200–218, 2017.

[57] J. Havukainen *et al.*, "Environmental impact assessment of municipal solid waste management incorporating mechanical treatment of waste and incineration in Hangzhou , China," *J. Clean. Prod.*, vol. 141, pp. 453–461, 2017.

[58] B. K. Sharma and M. K. Chandel, "Life cycle assessment of potential municipal solid waste management strategies for Mumbai , India," *Waste Manag. Res.*, pp. 1–13, 2016.

[59] Y. Liu, Z. Ni, X. Kong, and J. Liu, "Greenhouse gas emissions from municipal solid waste with a high organic fraction under different management scenarios," *J. Clean. Prod.*, vol. 147, pp. 451–457, 2017.

[60] J. D. Nixon, P. K. Dey, S. K. Ghosh, and P. A. Davies, "Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process," *Energy*, pp. 1–9, 2013.

[61] A. U. Zaman, "Life Cycle Environmental Assessment of Municipal Solid Waste to Energy Technologies," vol. 3, pp. 155–163, 2009.

[62] S. Yedla and N. T. Sindhu, "Assessment of alternative disposal methods to reduce greenhouse gas emissions from municipal solid waste in India," Waste Management & Research, Vol. 34. P. 553 –563, 2016.

[63] H. Tong, Y. Shen, J. Zhang, C. Wang, T. Shu, and Y. Wah, "A comparative life cycle

assessment on four waste-to-energy scenarios for food waste generated in eateries," *Appl. Energy*, vol. 225, May, pp. 1143–1157, 2018.

[64] M. Ibrahim, S. Ullah, A. G. Al-sehemi, and S. R. Ahmad, "Modeling the Higher Heating Value of Municipal Solid Waste for Assessment of Waste-To- Energy Potential: A Sustainable Case Study," *J. Clean. Prod.*, p. 125575, 2020.

[65] A. Emery, A. Davies, A. Griffiths, and K. Williams, "Environmental and economic modelling : A case study of municipal solid waste management scenarios in Wales," vol. 49, pp. 244–263, 2007.

[66] F. Fei, Z. Wen, S. Huang, and D. De Clercq, "Mechanical biological treatment of municipal solid waste: Energy efficiency, environmental impact and economic feasibility analysis," *J. Clean. Prod.*, 2018.

[67] J. D. Murphy and E. Mckeogh, "Technical , economic and environmental analysis of energy production from municipal solid waste," *Renew. Energy*, vol. 29, pp. 1043–1057, 2004.

[68] M. Rizwan, Y. Saif, A. Almansoori, and A. Elkamel, "Optimal Processing Route for the Utilization and Conversion of Municipal Solid Waste into Energy and Valuable Products," *J. Clean. Prod.*, 2017.

[69] M. Montagnana *et al.*, "Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil," *"Resources, Conserv. Recycl.*, vol. 87, pp. 8–20, 2014.

[70] S. Yi, Y. Jang, and A. K. An, "Potential for energy recovery and greenhouse gas reduction through waste-to-energy technologies," *J. Clean. Prod.*, 2018.

[71] T. L. Heng Chen, Jiarui Li, Tongyu Li, Gang Xu, Xi Jin, Min Wang, "Performance assessment of a novel medical-waste-to-energy design based on plasma gasification and integrated with a municipal solid waste incineration plant," *Energy*, vol. 245, p. 123156, 2022.

[72] S. Yedla and S. Kansal, “Economic insight into municipal solid waste management in Mumbai: a critical analysis,” *Int. J. Environ. al1li Pollution*, vol. 19, 2003.

[73] G.L. Sivakumar Babu P. Lakshmikanthan and L.G.Santhosh, “Life Cycle Analysis of Municipal Solid Waste (MSW) Land Disposal Options in Bangalore City,” no. November, 2014.

[74] A. Coban, I. F. Ertis, and N. A. Cavdaroglu, “Municipal solid waste management via multi-criteria decision making methods: A case study in Istanbul, Turkey,” *J. Clean. Prod.*, 2018.

[75] G. X. P. Zhenfeng Wang, Jingzheng Ren, Michael Evan Goodsite, “Waste-to-Energy, Municipal Solid Waste Treatment, and Best Available Technology: Comprehensive Evaluation by An Interval-valued Fuzzy Multi-Criteria Decision Making Method,” *J. Clean. Prod.*, 2017.

[76] S. Ting, H. Hashim, J. Shiun, W. Shin, C. Tin, and J. Yan, “Energy and emissions benefits of renewable energy derived from municipal solid waste : Analysis of a low carbon scenario in Malaysia,” *Appl. Energy*, 2014.

[77] R. L. Smith, D. Sengupta, S. Takkellapati, and C. C. Lee, “An industrial ecology approach to municipal solid waste management : II . Case studies for recovering energy from the organic fraction of MSW,” *"Resources, Conserv. Recycl.*, vol. 104, pp. 317–326, 2015.

[78] T. Silalertruksa and S. H. Gheewala, “A comparative LCA of rice straw utilization for fuels and fertilizer in Thailand,” *Bioresour. Technol.*, vol. 150, pp. 412–419, 2013.

[79] J. S. Mishra, N. S. Thakur, P. Sujathamma, B. B. Kushwaha, S. S. Rao, and J. V Patil, “Response of Sweet Sorghum Genotypes for Biomass , Grain Yield and Ethanol Production under Different Fertility Levels in Rainfed Conditions,” vol. 17, June, pp. 204–209, 2015.

[80] R. Singh, M. Srivastava, and A. Shukla, “Environmental sustainability of bioethanol production from rice straw in India : A review,” *Renew. Sustain. Energy Rev.*, vol. 54, pp. 202–216, 2016.

[81] S. Soam, M. Kapoor, R. Kumar, P. Borjesson, R. P. Gupta, and D. K. Tuli, "Global warming potential and energy analysis of second generation ethanol production from rice straw in India," *Appl. Energy*, vol. 184, April, pp. 353–364, 2016.

[82] M. Kami, M. Barz, S. H. Gheewala, and B. Sajjakulnukit, "Environmental and socio-economic feasibility assessment of rice straw conversion to power and ethanol in Thailand," *J. Clean. Prod.*, vol. 37, pp. 29–41, 2012.

[83] S. Soam, P. Borjesson, P. K. Sharma, R. P. Gupta, D. K. Tuli, and R. Kumar, "Life cycle assessment of rice straw utilization practices in India," *Bioresour. Technol.*, vol. 228, pp. 89–98, 2017.

[84] S. M. Sha, H. H. Masjuki, and T. M. I. Mahlia, "Life cycle assessment of rice straw-based power generation in Malaysia," Energy, vol. 70,P. 401-410, 2014.

[85] M. V. P. Migo-sumagang *et al.*, "Rice-Straw-Based Heat Generation System Compared to Open-Field Burning and Soil Incorporation of Rice Straw : An Assessment of Energy , GHG Emissions , and Economic Impacts," *Sustain.*, pp. 1–18, 2020.

[86] F. Chang, L. Lin, C. Ko, and H. Hsieh, "Life cycle assessment of bioethanol production from three feedstocks and two fermentation waste reutilization schemes," *J. Clean. Prod.*, 2017.

[87] S. Varjani, H. Shahbeig, K. Popat, Z. Patel, S. Vyas, and A. V Shah, "Sustainable management of municipal solid waste through waste-to-energy technologies," *Bioresour. Technol.*, vol. 355, April, 2022.

[88] M. Kami, M. Barz, S. H. Gheewala, and B. Sajjakulnukit, "Economic feasibility assessment of rice straw utilization for electricity generating through combustion in Thailand," *Appl. Energy*, vol. 88, 11, pp. 3651–3658, 2011.

[89] M. K. Delivand, M. Barz, and S. Garivait, "Overall Analyses of Using Rice Straw Residues for Power Generation in Thailand- Project Feasibility and Environmental GHG Impacts Assessment," pp. 39–46, 2011.

[90] N. Palmieri, M. B. Forleo, G. Giannoccaro, and A. Suardi, “Environmental impact of cereal straw management : An on-farm assessment,” *J. Clean. Prod.*, 2016.

[91] F. Raza, H. Khalid, W. Li, C. Chen, G. Liu, and R. Straw, “Enhanced methane production and energy potential from rice straw by employing microaerobic pretreatment via anaerobic digestion,” *J. Clean. Prod.*, vol. 296, p. 126434, 2021.

[92] T. T. Cuong, H. A. Le, N. M. Khai, and P. A. Hung, “Renewable energy from biomass surplus resource : potential of power generation from rice straw in Vietnam Central Highlands areas of Vietnam General Statistics Office of Vietnam Mekong River Delta areas of Vietnam,” *Sci. Rep.*, pp. 1–10, 2021.

[93] M. A. D. Noha Said, Adel Alblawi, Ibrahim Hendy, “Analysis of Energy and Greenhouse Gas Emissions of Rice Straw to Energy Chain in Egypt,” vol. 15, pp. 1510–1520, 2020.

[94] M. Ikhlayel, “A Systematic Life Cycle Thinking Approach to Develop Sustainable Municipal Solid Waste Management Systems for Developing Countries,” *J. Clean. Prod.*, 2018.

[95] A. U. Zaman, “A comprehensive study of the environmental and economic benefits of resource recovery from global waste management systems,” *J. Clean. Prod.*, 2016.

[96] V. Drosou, P. Kosmopoulos, and A. Papadopoulos, “Solar cooling system using concentrating collectors for of fi ce buildings : A case study for Greece,” *Renew. Energy*, vol. 97, pp. 697–708, 2016.

[97] R. L. Smith, D. Sengupta, S. Takkellapati, and C. C. Lee, “An industrial ecology approach to municipal solid waste management : I . Methodology,” *"Resources, Conserv. Recycl.*, vol. 104, pp. 311–316, 2015.

[98] R. L. Smith, “Hierarchical Design and Evaluation of Processes To Generate Waste-Recycled Feeds,” pp. 2508–2515, 2004.

[99] C. Dara, C. Hachem-vermette, and G. Assefa, “Life cycle assessment and life cycle costing of container-based single-family housing in Canada : A case study,” *Build.*

Environ., vol. 163, March, p. 106332, 2019.

[100] T. V Ramachandra, “Emissions from India ’ s transport sector : Statewise synthesis,” *Atmos. Environ.*, vol. 43, no. 34, pp. 5510–5517, 2009.

[101] M. N. Hossain, “Regionalized Life Cycle Inventory of Power Producing Technologies and Power Grids in India,” Chalmers University of Technology Gothenburg, Sweden, 2016.

[102] R. Kumar, “Life cycle assessment of rice straw utilization practices in India,” *Bioresour. Technol.*, 2016.

[103] P. Taylor, A. Dubey, and R. Lal, “Carbon Footprint and Sustainability of Agricultural Production Systems in Punjab, India, and Ohio, USA,” *J. Crop Improv.*, August 2013, pp. 37–41, 2009.

[104] US EPA, “United States Environmental Protection Agency.” Available: https://www3.epa.gov/ttnchie1/ap42/ch02/final/c02s01.pdf. [Accessed: 15-Dec-2017].

[105] S. Kumar *et al.*, “Specific Model for the Estimation of MethaneEmission from Municipal Solid Waste Landfills in India,” *Bioresour. Technol.*, 2016.

[106] F. Z. Siddiqui, M. E. Khan, J. Millia, and N. Delhi, “Landfill gas recovery and its utilization in India: Current status, potential prospects and policy implications Faisal,” *J. Chem. Pharm. Res.*, vol. 3, 5, pp. 174–183, 2011.

[107] P.U.Asnani, “Case Study: Pirana Landfill, Ahmedabad, India – An Assessment of the Potential for Methane Gas Recovery and its Industrial Applications,” 2015. Available: http://nswaienvis.nic.in/Waste_Portal/Case_Studies/cs_jun15/Case Study - Pirana Landfill, Ahmedabad.pdf. [Accessed: 28-Feb-2017].

[108] A. Kumar and M. P. Sharma, “Estimation of GHG emission and energy recovery potential from MSW landfill sites,” *Sustain. Energy Technol. Assessments*, vol. 5, pp. 50–61, 2014.

[109] A. S. E. Yay, “Application of Life Cycle Assessment (LCA) for Municipal Solid Waste Management. A Case Study of Sakarya,” *J. Clean. Prod.*, 2015.

[110] L. Postacchini, F. E. Ciarapica, and M. Bevilacqua, “Environmental assessment of a land fi ll leachate treatment plant : Impacts and research for more sustainable chemical alternatives,” *J. Clean. Prod.*, vol. 183, pp. 1021–1033, 2018.

[111] Y. Chen, J. J. Cheng, and K. S. Creamer, “Inhibition of anaerobic digestion process : A review,” *Bioresour. Technol.*, vol. 99, pp. 4044–4064, 2008.

[112] F. Muhayodin, A. Fritze, and V. S. Rotter, “A Review on the Fate of Nutrients and Enhancement of Energy Recovery from Rice Straw through Anaerobic Digestion digestion,” *Appl. Sci.*, vol. 10, 2020.

[113] A. Molino, F. Nanna, Y. Ding, B. Bikson, and G. Braccio, “Biomethane production by anaerobic digestion of organic waste,” *Fuel*, vol. 103, pp. 1003–1009, 2013.

[114] F. Xu, Y. Li, X. Ge, L. Yang, and Y. Li, “Anaerobic digestion of food waste – challenges and opportunities,” *Bioresour. Technol.*, September, 2017.

[115] M. Moretti, M. Van Dael, R. Malina, and S. Van Passel, “Environmental assessment of waste feedstock mono-dimentional and bio-refinery systems: Combining manure co-digestion and municipal waste anaerobic digestion,” *J. Clean. Prod.*, 2017.

[116] H. Y. Yap and J. D. Nixon, “A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK,” *Waste Manag.*, vol. 46, pp. 265–277, 2015.

[117] S. C. Bhattacharya and C. Jana, “Renewable energy in India : Historical developments and prospects,” *Energy*, vol. 34, pp. 981–991, 2009.

[118] Subhes C Bhattacharyya, “Energy access problem of the poor in India : Is rural electrification a remedy ?,” *Energy Policy*, vol. 34, pp. 3387–3397, 2006.

[119] MNRE, “Ministery of New and Renewable Energy Resources Goverenment of India , achivements. http://mnre.gov.in/mission-and-vision-2/achievements/ (accessed 25 February, 2018),” 2017.

[120] S. Unnikrishnan and A. Singh, “Resources , Conservation and Recycling Energy recovery

in solid waste management through CDM in India and other countries," *"Resources, Conserv. Recycl.*, vol. 54, pp. 630–640, 2010.

[121] DEA, "Department of Economic Affair, Ministry of Finance, New Delhi, Market development for clean energy sector : Focus on Municipal Solid Waste," 2008. Available: http://www.teriin.org/upfiles/projects/TOC/2008EE01_20101027120009.pdf.

[122] N. E. Joseph, "Scale-up of Deployment of Anaerobic Digester Technology at Public and Commercial Institutions : Challenges and Opportunities in India," TERI University New Delhi, 2015.

[123] S. S. N. C. K. A. K. N. and M. K. Kaushik, "Characterization of Municipal Solid Waste in Jalandhar City, Punjab, India," *J. Hazardous, Toxic Radioact. Waste*, vol. 17, pp. 97–106, 2013.

[124] MNRE, "Ministry of New and Renewable Energy, Standing Committee on Energy, Power Generation from Municipal Solid Waste," 2016. Available: http://164.100.47.193/lsscommittee/Energy/16_Energy_20.pdf. [Accessed: 01-Nov-2016].

[125] PMC, "Pune Munnicipal Corporaion, Integrated Solid Waste Managemnt (Energy revolution from municipal solid waste), Under Swachh Bharat Mission, Ministry of Urban Development Government of India," 2016.

[126] M. Berglund, "Environmental systems analysis of biogas systems — Part I : Fuel-cycle emissions," vol. 30, pp. 469–485, 2006.

[127] P. Singh, H. Gundimeda, and M. Stucki, "Environmental footprint of cooking fuels : a life cycle assessment of ten fuel sources used in Indian households," pp. 1036–1048, 2014.

[128] marianne thomsan Malene Nielsen, Ole-Kenneth Nielsen, *Emissions from decentralised CHP plants 2007 - Energinet.dk Environmental project no. 07/1882*, 2010.

[129] M. Waqas, A. S. Nizami, A. S. Aburiazaiza, M. A. Barakat, I. M. Rashid, and I. M. I. Ismail, "Optimizing the process of food waste compost and valorizing its applications: A case study of Saudi Arabia," *J. Clean. Prod.*, 2018.

[130] S. P. Gautam, A. K. Pandey, and M. K. Awasthi, "Municipal solid waste management in Indian cities – A review," vol. 1, pp. 591–606, 2010.

[131] A. K. Pramod Kumar Singh, Neetu Pandey, Monika Gupta, "Sustainable Municipal Solid Waste Management through Vermitechnology: Impact of Vermicompost on Sweet flag (Acorus calamus) plants and Sodic Degraded Land.," *Int. Adv. Res. J. Sci. Eng. Technol.*, vol. 2, no. 1, pp. 139–146, 2015.

[132] AECOM, "AECOM India Pvt Ltd, Environmental Impact Assessment Study,Common Municipal Solid Waste Management Facility Doddabidarakallu, Bengaluru," 2015. Available: http://kspcb.kar.nic.in/PH/Final EIA Doddabidarakallu_23062015.pdf. [Accessed: 15-Dec-2016].

[133] J. K. Saha, N. Panwar, and M. V Singh, "An assessment of municipal solid waste compost quality produced in different cities of India in the perspective of developing quality control indices," *Waste Manag.*, vol. 30, pp. 192–201, 2010.

[134] Z. Yang, X. Zhou, and L. Xu, "Eco-efficiency optimization for municipal solid waste management," *J. Clean. Prod.*, 2014.

[135] A. Bosmans, I. Vanderreydt, D. Geysen, and L. Helsen, "The crucial role of Waste-to-Energy technologies in enhanced land fi ll mining : a technology review," *J. Clean. Prod.*, pp. 1–14, 2012.

[136] UDD, *Urban Development Department Government of Maharashtra, Handbook of Technologies, Solid Waste Mangement*, First edition. Maharashtra, 2016.

[137] CPHEEO, "Central Public Health and Environmental Engineering Organisation, MUNICIPAL SOLID WASTE MANAGEMENT MANUAL PART II," 2016. Available: http://moud.gov.in/pdf/584e4b8b1e3da584e4a5c4a867Book2.pdf. [Accessed: 02-Jan-2017].

[138] CPCB, "Central Pollution Control Board, Selection Criteria for Waste Processing Technologies," 2016. Available: http://cpcb.nic.in/SW_treatment_Technologies.pdf. [Accessed: 25-Feb-2017].

[139] R. Rana, R. Ganguly, and A. K. Gupta, “An Assessment of Solid Waste Management System in Chandigarh,” *Electron. J. Geotech. Eng. 20 1547-1572.*, vol. 20, pp. 1547-1572., 2015.

[140] S. D. Regina Dube, Vaishali Nandan, Bineesha P, “Status Paper on Utilisation of Refuse Derived Fuel (RDF) in India,” 2010. Available: http://www.igep.in/live/hrdpmp/hrdpmaster/igep/content/e54413/e54441/e61172/e61173/20130425_RDFstatuspa. [Accessed: 15-Dec-2016].

[141] P. N. PRESSLEY, “Fuel Production from Municipal Solid Waste: A Life- Cycle Assessment,” North Carolina State University, 2013.

[142] B. Reza, A. Soltani, R. Ruparathna, R. Sadiq, and K. Hewage, “Environmental and economic aspects of production and utilization of RDF as alternative fuel in cement plants : A case study of Metro Vancouver Waste Management,” *"Resources, Conserv. Recycl.*, vol. 81, pp. 105–114, 2013.

[143] A. Ganesh and R. Banerjee, “Biomass pyrolysis for power generation - a potential technology Evaluation of options for energy recovery from municipal solid waste in India using the hierarchical analytical network process,” *Renew. Energy*, vol. 22, pp. 9–14, 2001.

[144] R. Singh and A. D. Setiawan, “Biomass energy policies and strategies : Harvesting potential in India and Indonesia,” *Renew. Sustain. Energy Rev.*, vol. 22, pp. 332–345, 2013.

[145] A. Kumar, N. Kumar, P. Baredar, and A. Shukla, “A review on biomass energy resources, potential, conversion and policy in India,” *Renew. Sustain. Energy Rev.*, vol. 45, pp. 530–539, 2015.

[146] S. Saini, P. Rao, and Y. Patil, “City based analysis of MSW to energy generation in India , calculation of state-wise potential and tariff comparison with EU,” *Procedia - Soc. Behav. Sci.*, vol. 37, pp. 407–416, 2012.

[147] K. Ghatge, “Pune Municipal Corporation, Energy Revolution From Municipal Solid

Waste," 2014. Available: http://icrier.org/Urbanisation/events/30-5-14/Waste_Energy_Ketaki Ghatge.pdf. [Accessed: 25-Dec-2016].

[148] MEDA, "Maharashtra Energy Development Agency, Tariff for supply of electricity from 4.87 MW capacity Municipal Solid Waste Power Project," 2013. Available: http://www.mercindia.org.in/pdf/Order 58 42/Order Case No 7 of 2012.pdf. [Accessed: 18-Dec-2016].

[149] A. U. Zaman, "Comparative study of municipal solid waste treatment technologies using life cycle assessment method," vol. 7, pp. 225–234, 2010.

[150] M. Sharholy and K. Ahmad, "Municipal solid waste management in Indian cities – A review," *waste Manag.*, vol. 28, pp. 459–467, 2008.

[151] CPCB, "Central Pollution Control Board, Ministry of Environment and Forests, Goverement of India. Municipal Solid Waste Management.," 2017. Available: http://www.cpcb.nic.in/Highlights/2008/chapter-11.pdf. [Accessed: 12-Nov-2018].

[152] T. and E. G. of P. Department of science, "Industrial and urban waste management in Punjab, Department of Science, Technology and Environment Government of Punjab.," 2015.

[153] C. Menke, S. Garivait, and B. Gadde, "Air pollutant emissions from rice straw open field burning in India , Thailand and the Philippines," *Environ. Pollut.*, vol. 157, pp. 1554–1558, 2009.

[154] IPCC, "Estimated Emission Factors For European Gasoline Passenger Cars. revised 1996 ipcc guidelines for national green house gas inventories: reference manual. https://www.ipcc-nggip.iges.or.jp/public/gl/guidelin/ch1ref5.pdf (accessed 14.02.2018)," 1996.

[155] E. Furuholt, "Life cycle assessment of gasoline and diesel," *Resour. Conserv. Recycl.*, vol. 3449, no. November 1992, pp. 251–263, 1995.

[156] P. Bhattacharyya, K. S. Roy, S. Neogi, T. K. Adhya, K. S. Rao, and M. C. Manna,

"Effects of rice straw and nitrogen fertilization on greenhouse gas emissions and carbon storage in tropical flooded soil planted with rice," *Soil Tillage Res.*, vol. 124, pp. 119–130, 2012.

[157] jyotika sood, "Not a waste until wasted. Down to Earth. http://www.downtoearth.org.in/content/not-waste-until-wasted (accessed 25 February 2018)," 2013.

[158] CERC, "Central Electricity Regulatory Commissionnew Delhi. Petition No. SM/03/2016 (Suo-Motu). http://www.cercind.gov.in/2016/orders/sm_3.pdf (accessed 11 January 2018)," 2016.

[159] S. Dasappa, D. N. Subbukrishna, K. C. Suresh, P. J. Paul, and G. S. Prabhu, "Operational experience on a grid connected 100kWe biomass gasification power plant in Karnataka, India," *Energy Sustain. Dev.*, vol. 15, pp. 231–239, 2011.

[160] M. K. Mann, P. L. Spath, C. P. System, M. K. Mann, and P. L. Spath, *Life Cycle Assessment of a Biomass Gasification Combined-Cycle System Life Cycle Assessment of a Biomass Gasification*. 1997.

[161] H. Liu, X. Yin, and C. Wu, "Comparative Evaluation of Biomass Power Generation Systems in China Using Hybrid Life Cycle Inventory Analysis," vol. 2014, 2014.

[162] M. Hiloidhari, D. Das, and D. C. Baruah, "Bioenergy potential from crop residue biomass in India," *Renew. Sustain. Energy Rev.*, vol. 32, pp. 504–512, 2014.

[163] R. Chandra, "Paddy Straw-based Power Fazilka District in Punjab Leading the Way !," *Energy Futur.*, no. July, 2016.

[164] R. Singh and A. D. Setiawan, "Biomass energy policies and strategies: Harvesting potential in India and Indonesia," *Renew. Sustain. Energy Rev.*, vol. 22, pp. 332–345, 2013.

[165] A. Waheed, K. Harijan, K. Qureshi, A. Ahmed, and A. Bahadori, "Perspectives for the production of ethanol from lignocellulosic feedstock e A case study," *J. Clean. Prod.*, vol.

95, pp. 184–193, 2015.

[166] A. Singh and A. Singh, "A comparative overview of Bio-ethanol production from Organic Residues of Agro waste Materials," March, pp. 11–14, 2015.

[167] R. K. Sukumaran *et al.*, "Lignocellulosic ethanol in India : Prospects , challenges and feedstock availability," *Bioresour. Technol.*, vol. 101, 13, pp. 4826–4833, 2010.

[168] J. Baeyens, Q. Kang, L. Appels, R. Dewil, Y. Lv, and T. Tan, "Challenges and opportunities in improving the production of bio-ethanol," *Prog. Energy Combust. Sci.*, vol. 47, pp. 60–88, 2015.

[169] The Economic Times, "Wealth from waste: A novel Indian biotech solution. https://economictimes.indiatimes.com/news/science/wealth-from-waste-a-novel-indian-biotech-solution/articleshow/52061459.cms (accessed February 25, 2018).," 2016. .

[170] CCEA, "Press Information Bureau Government of India Cabinet Committee on Economic Affairs, Cabinet approves revision of ethanol price for supply to Public Sector Oil Marketing Companies. http://pib.nic.in/newsite/PrintRelease.aspx?relid=151608 (Accessed 13 march," 2016.

[171] T. Silalertruksa and S. H. Gheewala, "Environmental sustainability assessment of bio-ethanol production in Thailand," *Energy*, vol. 34, pp. 1933–1946, 2009.

[172] A. Aden *et al.*, "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy02osti/32438.pdf (accessed 15 Februa," 2002).

[173] J. Moestedt and E. Nordell, "Biogas Production from Thin Stillage on an Industrial Scale—Experience and Optimisation," pp. 5642–5655, 2013.

[174] D. Mickael, "Categorization and Sorting for Waste Management," *Int. J. Waste Resour.*, vol. 6, 2016.

[175] A. Singh and P. Basak, "Economic and environmental evaluation of municipal solid waste management system using industrial ecology approach : Evidence from India," *J. Clean. Prod.*, vol. 195, pp. 10–20, 2018.

[176] A. Singh and P. Basak, "Modelling and simulation of PV-biogas based power generation system and its scopes of industrial applications: A case study on Punjab in India," in *7th India International Conference on Power Electronics (IICPE),* 2016, pp. 3–8.

[177] S. Singh, M. Singh, and S. Chandra, "Feasibility study of an islanded microgrid in rural area consisting of PV , wind , biomass and battery energy storage system," *Energy Convers. Manag.*, vol. 128, pp. 178–190, 2016.

[178] G. Liu, M. Li, B. Zhou, Y. Chen, and S. Liao, "General indicator for techno-economic assessment of renewable energy resources," *Energy Convers. Manag.*, vol. 156, November 2017, pp. 416–426, 2018.

[179] D. Karaboga and B. Akay, "A comparative study of Artificial Bee Colony algorithm," *Appl. Math. Comput.*, vol. 214, pp. 108–132, 2009.

[180] IRENA, *RENEWABLE POWER GENERATION COSTS IN 2019.International Renewable Energy Agency, Abu Dhabi*. 2019.

[181] A. Singh and P. Basak, "Economic and environmental evaluation of rice straw processing technologies for energy generation : A case study of Punjab , India," *J. Clean. Prod.*, vol. 212, pp. 343–352, 2019.

[182] B. Gadde, C. Menke, and R. Wassmann, "Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation," *Biomass and Bioenergy*, vol. 33, pp. 1532–1546, 2009.

[183] Ranjith Kharvel Annepu, "Sustainable Solid Waste Management in India," Columbia University, 2010.

[184] S. Arora, "Developing Suitable Selection Technique of Organic Food Waste Shredder of

Biogas Plant," *IJRSI*, vol. III, pp. 90–94, 2016.

[185] S. D. Regina Dube, Vaishali Nandan, Bineesha P, "Status Paper on Utilisation of Refuse Derived Fuel (RDF) in India," 2010. Available: http://www.igep.in/live/hrdpmp/hrdpmaster/igep/content/e54413/e54441/e61172/e61173/20130425_RDFstatuspa. [Accessed: 15-Dec-2016].

[186] Y. S. Yadav, "GENERATION OF GREEN ENERGY FROM PADDY STRAW A NOVEL INITIATIVE IN SUSTAINABLE AGRICULTURE," *Akshay Urja*, pp. 30–33, 2016.

[187] S. M. Saon Ray, Amrita Goldar, "Ethanol blending policy: Issuses related to pricing," *ICRIER Policy Ser.*, vol. 10, pp. 1–25, 2011.