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Intelligent Power Generation from Anaerobic Digestion of Municipal Solid Waste: A Case Study of Faridabad, India

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Abstract. This paper proposes a power generation system using Municipal Solid Waste (MSW). Organic fraction of MSW is subjected to anaerobic digestion and the biogas obtained is supplied to Solid Oxide Fuel Cell (SOFC) for power generation. As SOFC is a high temperature fuel cell, heat ie. hot air and steamobtained is utilized for pretreatment of MSW, maintaining temperature of digester, partial reforming of biogas and drying of digested slurry. The digested slurry obtained is useful as fertilizer and covers major cost of biogas system. The proposed system is studied in district Faridabad, India for economic feasibility. Faridabad produces 723.9 MT MSW per day which gives 289 to 325 MT of organic matter for anaerobic digestion. Available MSW is divided in four parts across the district. System is simulated in Homer in grid connected mode with each one part producing 21900 MWh annually (making total production from four plants as 87600 MWh) with Levelized cost of energy USD 0.0299 per kWh and the dried digested slurry gives 5840 MT fertilizer annually. Emissions from the system are much lower than conventional thermal power plants and landfilling.

Keywords: *Municipal solid waste, anaerobic digestion, pretreatment, biogas, solid oxide fuel cell.*

1. Introduction

Increase in population in industralized and metropolitan cities is causing an increase in Municipal Solid Waste (MSW) in these areas which is becoming difficult to manage. Mismanaged MSW is adversely affecting the environment and helath of the nearby residents. MSW consists of organic materials, recyclable materials and inert matter which are disposed to landfill sites. Degradation of organic or biodegradable matter emits methane which is imflammable and is a prominent green house gas (GHG). As per [1] at landfill sites one tonne of organic waste emits 400 kg CO2 eq. Conditions at landfill sites enables breeding of disesase causing organisms which spread asthma, cholera, malaria, diarrhoea, tuberculosis, reoccuring flue and skin irritation [2]. Water and other fluids or moisture present in the landfill area produces leachate which gradually passes through the disposed waste,accumulates contaminants and effects groundwater.

Another issue related to increase in population and expansion of economies is the increased requiement of energy. Conventional resources dominate power generation sector which adversely effects environment, health and ecosystem. Depleting stocks of fossil fuels is another big reason for search of alternate or renewable fuels.

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Municipal solid waste (MSW) can be used as renewable fuel for generating electricity either by incineration in waste to energy power plants or can be used to produce biogas by anaerobic digestion. Average heating value of MSW is 10 MJ/kg [3] which can be incenerated in thermal/waste to energy power plants reducing the waste volume by 75%. Biogas is used in boiler for producing steam which runs the generator via turbine. In another approached biogas powered engine is connected to generator. Recent and more efficient approach is to use biogas as fuel for fuel cell thereby producing electricity. [4] analyzed the energy potential of MSW in Ilorin, Kenya. Daily 584 tons of MSW was available which gave 3244 MWh energy availability and electric potential of 41 MW. [5] compared techniques of direct combustion, gasification, anaerobic digestion and landfilling from MSW in three cities of Colombia. Highest value of Internal rate of return for landfill gas was 13.59% and for anaerobic digestion was 14.27%. [6] studied 14.9 MW waste to energy power plant in Ahmedabad using 1000 tons of MSW used per day for electricity generation. After incineration 75% of MSW was reduced and the power generated was equal to that produced by 417 tons coal per day reducing GHG emissions of 300 tCO2 eq/day. [7] studied GHG emission in WTE plants using 24650 t MSW and industrial waste in Taiwan. GHG emission from incineration of MSW including plastic, paper, textile and rubber waste was 952.61 Gg CO2 eq/yr with plastic waste as maximum emitter, and the plants generated 7394.13 * 10^6 kWh energy in a year. Another approach is the use of Solid Oxide Fuel Cells for power generation. [8] proposed a SOFC and gas turbine hybrid power generating system in Tehran, using MSW for producing biogas which powered SOFC. Heat in SOFC was further utilized to run gas turbines for producing electricity thereby increasing the system efficiency. With 997.3 toms of biogas available in a day, SOFC generated 300 MW power with per unit energy cost as $ 0.178. Adding gas turbine system increased power generation to 525 MW and cost reduced to $ 0.11 per kWh.

This paper considers SOFC for power generation using biogas produced from anaerobic digestion of organic part of MSW. The digested slurry is having good nutrition value making it suitable for use as fertilizer for agriculture purposes thereby making circular economy. High heat in SOFC is used for pretreating of organic matter so as to increase biogas production. A case study of district Faridabad, India is done considering the MSW available, it's collection, segregation, production of biogas, fertilizer, electricity and emissions. An economic analysis of the system is done to determine economic feasibility.

2. Solid Oxide Fuel Cell

Fuel cell is a electrochemical energy conversion device that continuously converts a part of free energy change in a chemical reaction to electrical energy. Solid oxide fuel cells (SOFC) uses solid non porous metal oxide usually Y2O3 stabilized ZrO2. The cell operates at 600-1200 ºC where ionic conduction takes place [9]. Their efficiency is about 60% but due very high operating temperature they have a good scope for combined heat and power plant which increases the efficiency from 85 – 90%. Oxidation at anode and reduction at cathode is given by equations (1) and (2):

At anode: $H_2 + O^{2-} \rightarrow H_2O + e^-$………….. (1)

At cathode: $\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$………………(2)

Hydrocarbons like purified coal gas, natural gas, biogas, methane etc. can be used as fuel.

Due to innovations in technology and product improvements the price of fuel cell is continuously declining for the past years and is expected to further decrease in the future as well. All the costs are taken in USD ($)(= 82.39 Indian Rupee). As per [10] the decline in the cost of per unit electrical energy ($/kWe) will decreased from 5700 $/kWe in 2020 to 980 $/kWe by 2030with increase in cumulative installed capacity (MWe) from 1 to 1000 Mwe installed capacity. The decrease in the cost of fuel cell stack for different electrical ratings (in kWe) with increase in production volume is shown in table 2 [11]

Table 1. Cost of fuel cell stack with increase in production at different eletrical ratings

Systems per year	*1 kWe*	*10 kWe*	*50 kWe*	*100 kWe*	*250 kWe*
100	5386.89	1039.32	477.59	339.06	249.12
1000	1195.51	342.34	214.77	194.38	180.52
10000	451.38	196.66	176.42	170.86	167.25
50000	322.04	178.33	169.71	167.24	165.88

Also the cost of material for electrode -electrode assembly ($/kWe) decreases with increase in the annual production volume (Mwe/year) as in fig. 1

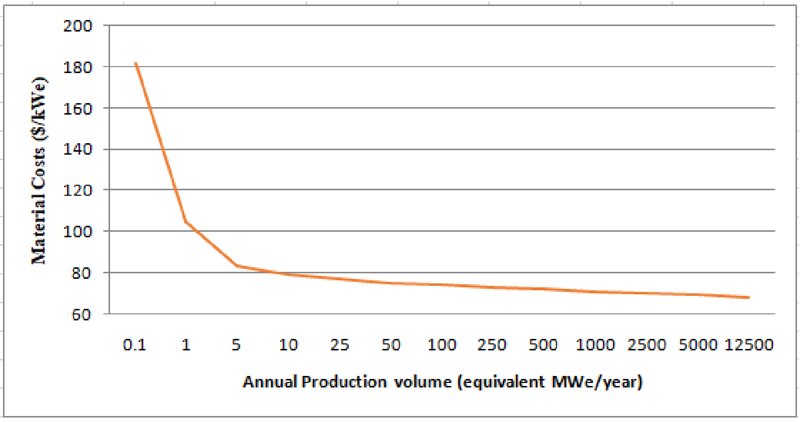

Fig. 1 Decrease in material cost for electrode-electrode assembly with increase in annual production

3. Biogas Production

Biogas is produced by anaerobic digestion. Anaerobic digestion process involves breakdown of complex structure of organic waste by micro organisms in the absence of oxygen. Biogas consists of 50-75% methane. Biogas has a calorific value of about 31 to 23.5 MJ/m³ ie. 1 of biogas has energy content equal to 6 kWh (for 100% efficient conversion system). Biogas can be used for cooking, lighting and electricity generation. Also by purifying, it can be used in biogas engines for locomotives, for driving generators and producing electricity thereby replacing diesel in diesel-generator sets; also this purified biogas can be used in fuel cell for producing electricity. Biogas obtained from different types of substrates is given in table 2.

Table 2. Biogas produced from different types of substrates [12]

Type of biomass	Biogas (m³/MT) fresh matter
Tomato residue	101.8±18.7
Potato residue	126.8±3.5
Vegetable, fruit and legume waste	158.1±18.7
Beet pulp	104.5±13.6
Grapes and vinasses	150.0±12.1
Slaughterhouse waste	102.5±0.4
Edible oil residues	301.0±9.3
Crop/Agriculture residue	124.4±4.9

Municipal solid waste (MSW) consists of 40-45% organic matter, 20-30% inert matter and rest is recyclable matter. Different types of organic wastes like food processing waste, garden, kitchen, food waste and paper pulp consists of cellulose, hemicelluloses and lignin bonded together forming lignocelluloses. The complex and rigid structure of these lignocelluloses wastes is a big hindrance in anaerobic digestion. Pretreatment of such wastes is needed for breaking down the complex structure and maximizing the biogas production. Different types of processes like physical, chemical, physiochemical and biological process are use or are researched [13].

In physical treatment the size of the particles is decreased which increases the surface area and breaks the rigid structure. Physical treatment is environment friendly but is energy consuming. [14] studied the energy consumed on physical pretreatment of softwood and hardwood. For softwood the energy consumed was ranging from 11 to 27.6 kWh/metric tons and for hardwood it was 85.4 to 118.5 kWh/metric tons. In a study by [15] particle size of 8 to 13 mm gave higher enzymatic digestibilities when subjected to steam explasion whereas use of smaller sized particles (from 2 to 8 mm) was not optimal.

In steam explosion, the organic material or biomass is treated with high pressure (0.69 to 4.83 Mpa) and high temperature (160 to 260 ºC), the pressure is then suddenly released causing rupture of the rigid bonds. This method is environment friendly, efficient and does not requires chemicals. Milled small sized particles subjected to steam explosion does not requires any type of chemical treatment [16]. Instead of steam, water can be used at temperature of 170-230 ºC and pressure of 5 MPa. This pressure avoids evaporation of water. In this method sudden release of pressure is not needed. Pretreatment using hot water does not needs catalyst, no toxic materials are formed and is independent of particle size making it feasible for large scale [17]. As the process uses high quantity of water and so consumes large power. In a study by [18] hydrothermal pretreatment gave twice the amount of methane (132.7 L/kg volatile solid) than in untreated rice straw; the increase was 61% when pretreating alperunjo with steam at temperature of 200 ºC and 1.57 Mpa pressure [19] and pretreatment of grass at 80 ºC for three days increased methane yield by 46% [20].

4. Proposed System

The organic matter, inert matter and recyclable matter are seperated using segregator. Organic matter is milled into smaller sized particles using miller and it's complex structure is broken down using the process of steam explosion. This pretreated organic matter is a suitable substrate for anaerobic digester. The feedstock is mixed with approximately equal quantity of water and fed to anaerobic digester which produces biogas and digested slurry. Biogas is purified for hydrogen sulphite and siloxanes impurities and stored. Biogas is used as fuel SOFC but having higher amount of methane causes carbon deposition at anode and so reduce the amount of methane and increase hydrogen, reforming is done. For steam methane reforming process, a part (50% by vol.) of steam obtained from anode is utilized and reaction taikng place is shown in equation (3) as:

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \quad \text{.................... (3)}$$

SOFC takes place at high temperature (800 ºC) and this temprature can be utilized for enhancing the performance of the system. Alongwith steam a part of the hot gas from cathode is supplied to afterburner which provides heat to pre-heater and a part of this heat is supplied to air preheater. Air preheater provides hot air to cathode and heat to boiler. The boiler provides steam for the steam explosion of MSW which enhances it's digetibility. Also a part of the heat from the boiler is utilized for maintaining temperature of the boiler and in drying of digested slurry. Maintaining suitable temerature of digester (37 ºC) maximizesbiogas production even at low environmental temperature. Fig. 2 showsthe system with temperatures at each component. Sensible heat in stream j (Q_j) is given by equation 4

$$Q_j = \Sigma f_i * q_i \text{.......................(4)}$$

where, f_i is molar flow of component i

q_i is molar sensible heat of component i at temperature T_j

q_i is given by equation (5)

$$q_i = \int_{T_{ref}}^{T_j} C_p^i \, dT \text{ ....(5)}$$

where, T_{ref} is reference temperature (= 298.15 K)

C_p^i is specific heat capacity at constant pressure C_p

C_p^i for different compounds like methane, carbondioxide and steam is given by equation equation (6) [21]

$$C_p^i = \frac{(a+b*T+c*T^2+d*T^3)}{1000} \text{.............(6)}$$

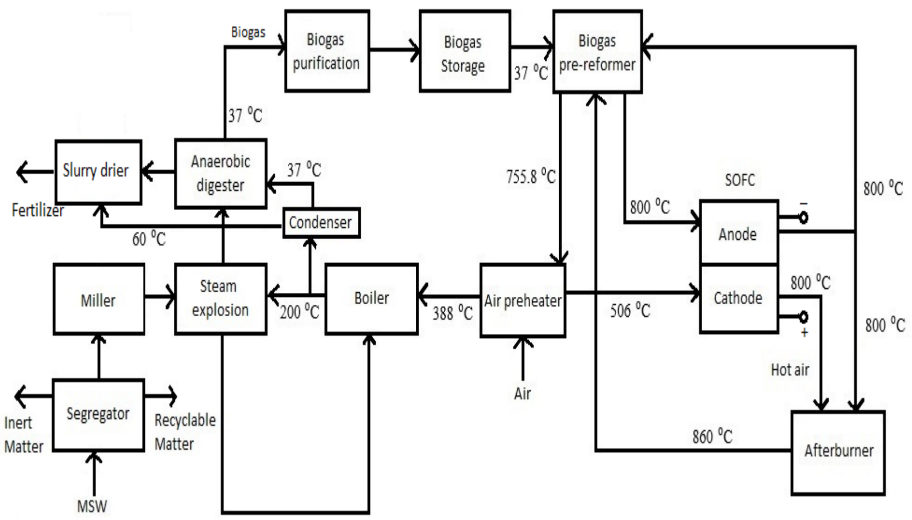

Fig.2 Proposed biogas powered fuel cell based power plant

5. Case Study of Faridabad

Faridabad is spread in 741 sq km area having 144 villages and population of 1809733. Per person 0.4 kg of MSW is generated everyday which gives 723.9 MT per day. Waste collected by Municipal corporation Faridabad is dunped at Bandhwari landfill site. Alongwith Faridabad, the same 30.5 acre landfill site is used by neighboring Municipal Corporation Gurugram. The landfill is already overloaded and Faridabad is allotted another landfill site at nearby area Pali, but the residents of that area are opposing it. An waste to energy power plant is to be build up at Bandhwari which is expected to be operational by Dec 2023. Waste management is a big problem. Being industrial hub, the electricity consumption of Faridabad is also high, the annual electricity consumption is expected to reach 69613 lakh units by 2024, 90497 lakh units by 2027 and 117646 lakh units till 2030 [22]. District is not having coal and water resources and MSW can serve as locally available renewable resource. Government of Indias' Ministry of New and Renewable Energy started "Programme on Energy from Urban, Industrial and Agricultural Wastes/Residues" which provides financial assistance of $ 91,030 per MW for power generation from new biogas plant and $ 60,686 per MW for power generation from existing biogas plant with maximum assistance of $ 6,06,869 per project for both cases [23].

5.1 MSW collection and processing

Currently MSW is collected by Municipal Corporation Faridabad (MCF) and in some areas private contractors are employed for collecing waste from each household. After collection of waste by MCF and private contractors, a team of employees from the power plant also are needed for waste collection as still a big amount of MSW is disposed off in open areas. This action will ensure maximum waste collection. Total 741 sq km area is divided in four zones of 185.25 sq km each having it's own power plant. Four workers with vehicle for every 37 sq km area are assigned for waste collection and 5 such groups are formed in each zone.

The proposed system consists of waste segregation unit, pretreatment unit, digester, gas storage balloon, purification system, online monitoring system, fuel cell, heat recovery system, slurry drying and packaging unit. As the process starts with waste segregation, with 40-45 % as organic matter, 20-30% inert matter and rest inert matter gives 180.98 to 289 MT recyclable material and 144.8 to 217.2 MT inert matter [24]. Taking the average value of different types of wastes as in table 2 and considering the effect of pretreatment total biogas produced is given in table 3.

Table 3. Biogas produced as per MSW collected

% MSW collected	Organic waste available (MT)	Biogas produced (m^3)
100%	289.56 to 325.78	63003.62 to 81465.86
90%	260.6 to 293.18	56702.38 to 73313.76
80%	231.65 to 260.6	50403.33 to 65166.67

Maximum capacity goes upto 81,465.86m^3 biogas which is purified and stored.

5.2 Calculating the size of digester

Considering the maximum collected organic waste ie. 289.56 to 325.78 MT. Fig 3 shows four areas considered in district Faridabad for MSW collection and further processing; each area is having 81 MT of organic waste.

This feedstock is pretreated and mixed with equal quantity of water giving total of 162 MT slurry. Considering the standard density of 1090 kg/cu m.

The volume of daily charge = weight of slurry / density

ie. $V_d = 162000/1090 = 148.6 m^3$………………………………….(3)

Volume of the digester = 1.1 x Vd x retention time (= 25 days)

Volume of digester = 1.1 x 148.6 x 25 = 4086.5m^3 …………...………….. .(4)

If D is the diameter and H the height of the digester then

Volume = $\Pi/4\ D^2 H$

For community plant the digester's diameter to height ratio is 1.

This gives $H^3 = 4 \times Volume/\Pi$

So $H^3 = 4 \times 4086.5/ 3.14$ ……………………………………….(5)

This gives H = D = 17.3 m

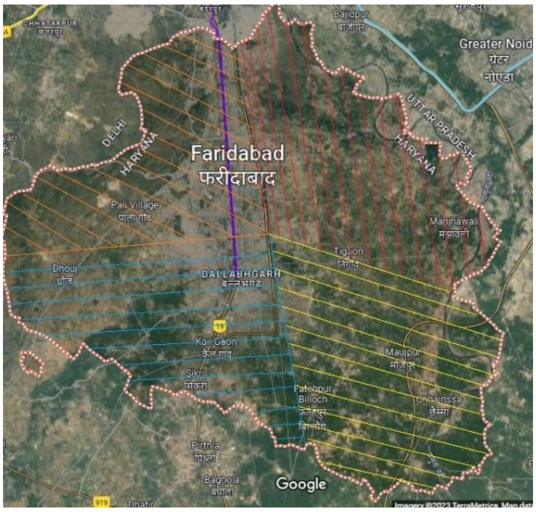

Fig. 3 Satellite map of district Faridabad divided in four areas for MSW collection and processing

Considering the top area for small scale gas collection as 510 m³. From here biogas is taken out and stored in large balloons from where it is fed to SOFC for electricity generation. Higher manpower is employed so as to collect whole 100% of MSW giving average value of biogas produced (between 63003.62 to 81465.86 for maximum waste collection) which approximates to be 72234 m³ (or 18058 m³ from each of the four plants).The digested slurry obtained is dried and used for agriculture purposes. Considering 80% as the water content, 16 MT of fertilizer is obtained every day from each plant.

5.3 Economic Analysis of Biogas Producing System

Taking references from section 2, [25], manufacturers catalogues, vendors and e-commerce websites, the different costs involved in one plant are given in table 4:

Table 4. Different costs involved in biogas productiion system in first year of installation

S.No.	Assets/Equipments	Cost (in $)
1.	Plant machinery	
	MSW segregator (5 HP, capacity 5 ton per hour, 440 V)	55043.09
	Organic matter milling machine (75 HP capacity 15 tons/hour)	17599.22
	Steam explosion reactor (25 L)	788.93
	Anaerobic digester (CSTR type) + purifying system	242747.91
	Biogas collection balloons (13000) m³	21410.36
	Heat exchanger/Boiler	2854.96
	Biogas pre-reformer	18206.1
	Afterburner	424.8
	Air preheater	728.24
	Condenser	1213.74
	Slurry drier	1820.69
	Controlling and auxiliary equipments	12137.39
2.	Cost of operation & salary of employees	356523.85

	Total	1004345 approx.

Table 4 gives the costs involved in installation and annual running costs in first year of plant installation. Similarly, costs and earnings from other three plants can be obtained. This data can be extrapolated for twenty years. The components used have life ranging from 10 to 15 years, after which they will be replaced. Daily 13001 kg (density is 0.72 kg/m³) biogas and 16 MT fertilizer is produced. Fertilizer sold at a price of $ 0.06/kg gives earning of $ 780 in a day which gives major part of earning from the biogas producing system. The cost of biogas is reduced considerably to $ 0.012 per kg.

Segregated matter consists of recyclable materials and inert matter. Inert matter consists of sand, construction and demolition wastes which after minor processing can be reused for construction purposes at a cost of approximately $ 8.5 per MT. Recyclable materials include metals, plastics and glass. Metal mostly includes aluminium (cost $ 2.09 per kg) as costly metals like copper ($ 8.44 per kg) are are in very less quantity in MSW. Plastics are present in a big amount in MSW, different types of plastics are having different prices ranging from $ 0.3 to $ 0.6/kg like PVC ($ 0.45/kg). Glass is another recyclable material found in MSW which can be sold at $ 0.121 /kg.

5.4 Simulation Results of power generation system

For simulation, discount rate is taken as 4.9, inflation rate as 4%, annual capacity shortage is taken as 5% and project life is 20 years. Table 5 shows the initial capital, replacement, opertion, maintenance costs and lifetime of differnet components used in the power generating system.

Table 5. Cost of different components in power generating system

Component	Capital (in $)	Replacement (in $)	O&M (in $)	Lifetime
PV module (per kW)	473.36	425	4.7/year	25 years
FC (per kW)	249	249	0.03 /hour	50000 hours
Converter (per kW)	36.41	36.41	3.64/year	15 years
Biogas Tank (per kg)	15.17	15.17	1.5/year	20 years
Microgrid controller	50000	50000	100.0	25 years

The proposed system is simulated in Homer software, fig 3. shows the grid connected system and results obtained for a daily average industrial load of 40900 kWh/day, fig. 4 shows optimized results obtained from simulation the fuel cell system in grid connected mode and the optimal ratings and economic parameters are shown in table 5, table 6 gives the emissions from the power generation system.

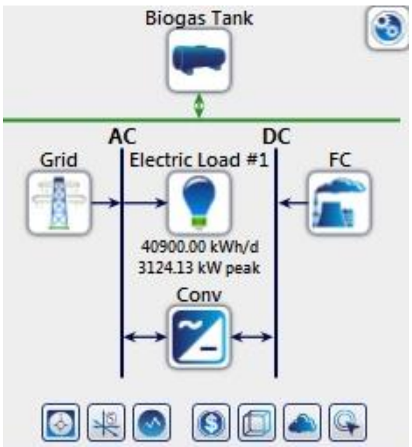

Fig 3. Grid connected power generation system

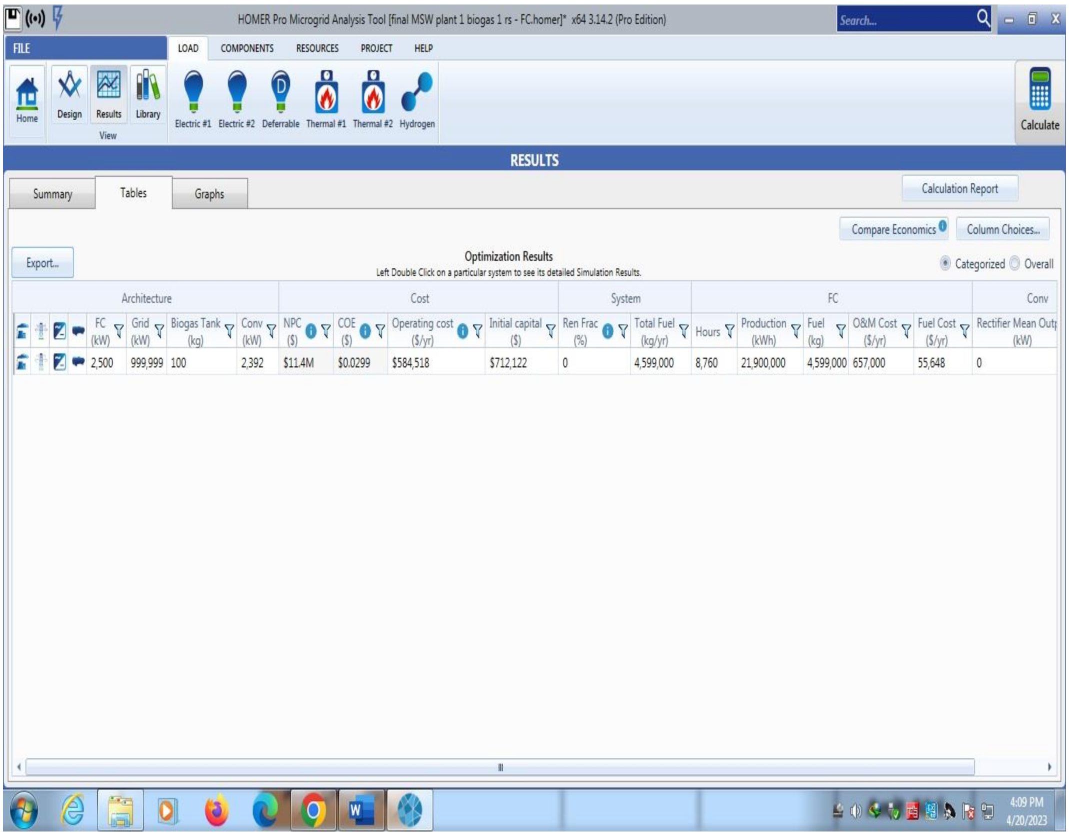

Fig 4. Simulation results obtained from Homer

Table 5. Results indicating optimal ratings and economic parameters for simulated power system

Optimal ratings		
S.No.	Component	Rating/Capacity
1	Fuel Cell	2500 kW
2	Inverter	2392.3 kW
3	Biogas tank	100 kg
Economic parameters		
S.No.	Quantity	Amount in $
1	COE	0.0299
2	NPC	11404430
3	Annual operating cost	584518.3
4	Initial capital	712121.5
FC system		
S.No.	Quantity	Rating/amount
1	Yearly working	8760 Hours
2	Annual production	21900000 kWh
3	Fuel consumption	4599000 kg
4	Annual O&M cost	657000 $

Table 6. Emissions from power generation

S.No	Quantity	Value	Units
1	Carbon dioxide	3,70,507	Kg/yr
2	Carbon monoxide	920	Kg/yr
3	Sulfur dioxide	150	Kg/yr
4	Nitrogen Oxides	166	Kg/yr

The emissions are 20.43 * 10^6 kg/CO2 eq reduced as compared with conventional coal based power generation [26] and 47.19 * 10^6 kg/CO2 eq reduced as compared with landfilling.

All the four systems will together produce 87600 MWh energy annually which fulfills 1.26 % of the district's electricity requirements

6. Conclusion

In this study, MSW is evaluated as renewable source for power generation. On segregation MSW gives organic matter, recyclable matter and inert matter. Anaerobic digestion of organic matter gives biogas and fertilizer. Fertilizer is a source of earning and returns nutrients back to soil when used for agricultural purposes. Recyclable and inert matter are also processed and reused making full utilization of MSW and forming circular economy. On the other hand incineration of MSW despite giving higher energy than biogas, gives ash as byproduct which is further used. Biogas is used as fuel in SOFC, high temperature of SOFC is utilized for pretreatment of organic waste and maintaining optimal temperature of anaerobic digester which in turn increases biogas production.

Larger area is divided in smaller subareas and more staff employed increases MSW collection efficiency. Simulating the system onsidering higher amount of biogas produced and the earnings from fertilizer, cost of energy is reduced and comparable with utility mains and emissions are lesser than conventional generating systems. The proposed system solves two problems ie. waste management and energy requirement.

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