



## Exergetic Analysis of a Microalgae Gasifier with an Integrated Solar Dryer

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### ABSTRACT

Renewable energy sources are rapidly substituting fossil fuels. In this paper, energy and exergy analyses of microalgae biomass to synthetic gas production is presented. First and second laws of thermodynamics analyses were conducted on three energy systems: solar dryer; combustor; and a gasifier. Exergy analysis was performed on three heat media to investigate the energy conversion performance of each energy system within range of 10-50% humidity. The tests were carried out on three conditions: product gas having high concentrations of carbon monoxide and hydrogen gases; gasification begins at 1000 °C; and complete combustion with no ash formation. According to the results obtained, moisture content in microalgae biomass has negligible effect on the exit temperature of synthetic gas from gasification chamber. The exergy loss analysis in solar dryer show lower values compared to a combustor and gasifier. The gasifier chamber is least energy efficient system with exergy loss value of 5.4KJ/Kg at 50% humidity compared to 3.4KJ/Kg and 3.1KJ/Kg at 50% humidity levels for solar dryer and combustor respectively.

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### INTRODUCTION

Algae gasification is a thermo-chemical process of converting carbonaceous biomass into synthetic gas (Dalwadi, 2016). The technology has been fully developed for coal gasification (Wu *et al.*, 2002). With environmental issues associated with greenhouse emissions from fossil fuel, enormous interest have been directed towards biomass fuels characterized by low carbon dioxide emissions (Damiani, 2014). Microalgae and other biomasses like agricultural products are enormous and readily available for power conversion (Ali N., *et al.*, 2015; Jacobson, 2019) however, due to low

technological advancements these resources are not fully articulated for electricity generation; algae biomass presents good development platform for power generation technology (Wu *et al.*, 2002; Enamala *et al.*, 2018). With the global energy shift towards renewable energy sources due to burgeoning human population, gasification technology has been utilized to produce biofuels from plant biomass (woodchips, algae, household waste) (Datta, 2019). According to Sikarwar *et al.*, (2017), it revealed that biofuels produced from gasification needs no modification and can easily blend with fossil fuels, with the technology fully deployed in



North America in the transportation industry (Jacobson, 2020). Like other thermal conversion processes, gasification offers rapid conversion rate than liquefaction although both are utilized to produce bio-oil and bio-gas respectively (Barros, *et al.*, 2015). Gasification produces less air pollution unlike biomass combustion with high CO<sub>2</sub> emissions (Ahmad, *et al.*, 2018; Jacobson, 2019). Complexity of the technology arises from high salt contents in biomass that leads to corrosion and blockage along with the presence of undesirable quantities such as moisture, nitrogen, sulfur and metal contents make conversion challenging (Verma *et al.*, 2011). Burning biomass at 1100 K – 1330 K in air or steam converts solid and liquid biomass into high values calorific products which are odourless, colourless and easily burn in heat engines due to low calorific value of 4-6 MJ/m<sup>3</sup> (Higman, 2003). The conversion starts with drying at 300 K, thermal cracking (pyrolysis) at 600 K and gasification at 1000 K (Sandeep, 2014).

In a research conducted by Parvez (2014), it revealed that by 2050 biomass would provide 38% and 17% of world's direct fuel and electricity respectively. Additionally, Puig-arnavat, *et al* (2010), reviewed thermodynamic and kinematic analyses on various biomass gasification models with the results proved to be useful in performance evaluation of various gasifier systems. Saidur, (2012) conducted a study on the exergy analysis of biomass based fuels and the results revealed gasification process as the most effective thermochemical route of biomass

conversion to fuels. Similarly, integration of biomass gasification with power generation has not just great market potential in utilizing biomass to generate electricity of 1 MW range using circulating fluidized bed (CFB) gasification process, it also offers an efficient pathway in converting household wastes into useful gases (Wu *et al.*, 2002; Tang *et al.*, 2019).

With current state of technological advancements, several renewable energy projections have been made: International Renewable Energy Agency (IRENA) 2014 roadmap report stated that the global renewable energy share will exceed 30% in 2030 from the current 18% with biomass accounting for 75% of total renewable energy consumption. The study identifies a doubling rate of energy efficiency of 36% with increase in technology improvement and universal access to modern energy services (Amin, 2014). British Petroleum, (Bp) 2019 energy outlook report revealed that renewable share index for power generation will stand at 29% (wind 13%, solar 12%, biomass and geothermal 3%) by year 2040. Ostensibly, these figures project Africa to have 6% of world's energy demand with a quarter of world's population by year 2040. Environmental issues due to increasing human population will become a leading driver to green revolution with gasification technology as an alternative route to produce cleaner and environmentally friendly gases when compared to coal gasification as seen in Table 1. ( Puig-arnavat, *et al.*, 2010; Ahmad, *et al.*, 2018)

**Table 1:** Flare stack emission comparison Properties (Revision, 2011; Bello, 2014)

Parameters	Biomass Gasification	Coal gasification
Sulfur content	Below 0.1%	Above 1%
Lower heating Value	18 -22 MJ/kg	30MJ/kg
Oxygen content	Above 40%	Below 10%

## MATERIALS AND METHOD

### Materials

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This study utilized conservation of energy and mass equations and modeling programs (Autocad, Microsoft office and Matlab) to evaluate energy utilization efficiencies of a solar dryer, a combustor and a gasifier unit.

**Method**

An indirectly-heated gasifier chamber with heat delivered from microalgae combustor integrated with solar dryer is illustrated in Figure 1. The energy conversion process is predicated on

renewable energy sources (solar dryer and combustion of feedstock). Energy and exergy analyses were conducted on energy media which consist of: a solar dryer (for dehumification of wet algae biomass), a combustion chamber for burning dry algae feedstock to provide heat for the gasification process and a gasifier chamber (converts feedstock into synthetic gas). The gasification process is endothermic with heat supply from combustion for dry algae feedstock as shown in figure 1.

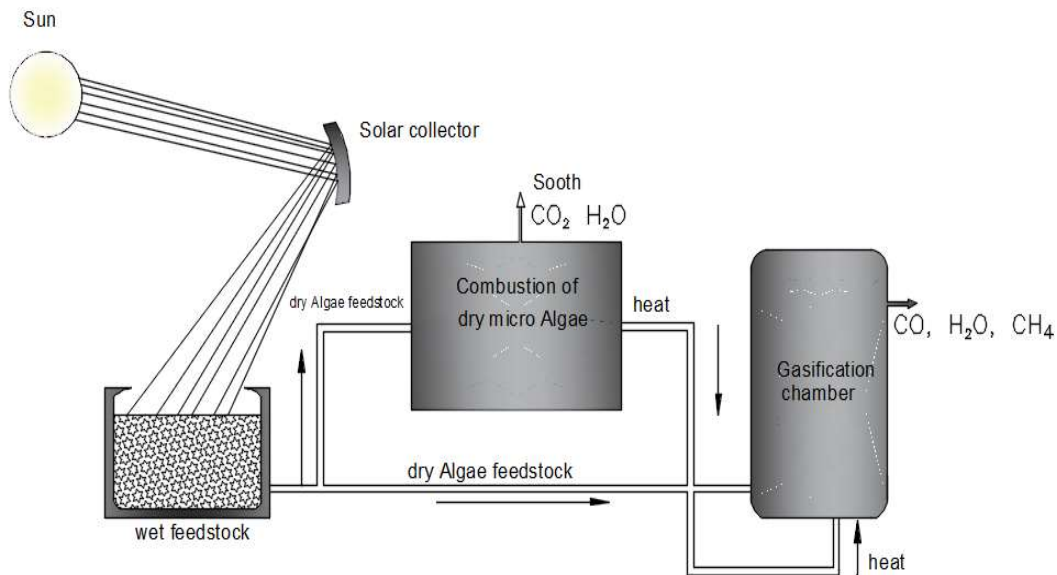


Figure-1 Schematic Solar Dryer Biomass Gasification

**ENERGY AND EXERGY ANALYSIS ON SOLAR DRYER**

**Energy Balance on Solar Dryer**

Applying steady state energy equations on solar dryer, the radiant energy ( $Q_{rad}$ ) required to dry wet algae feedstock with varying moisture contents of 10 – 50%

and temperature range of 27 °C - 400 °C is given by equations 1 and 2. Additionally, equation 2 also estimates the area ( $m^2$ ) required taking the assumption of one (1) hour for complete drying of wet feedstock.

*From first law of thermodynamics and applying steady flow*

$$Mass_{in} = Mass_{out}$$

$$Energy_{in} = Energy_{out}$$

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$$Q_{radiation} + (M_{1\ wat} \times h_1 + M_{1\ dry\ feed} \times h_1) = (M_{2\ wat} \times h_2 + M_{2\ dry\ feed} \times h_2)$$

Eqn. (1)

$$Q_{radiation} = [M_{dry\ feed}(h_{2\ sensible} - h_{1\ sensible}) + M_{wat}(h_{400^0} - h_{27^0})]$$

$$Q_{rad} = [M_{dry\ feed}C_p(T_2 - T_1) + M_{wat}(h_{400^0} - h_{27^0})]$$

Eqn. (2)

**Exegetic Balance on a Solar Dryer**

Exergy loses while drying wet algae feedstock within the range of 10-50% humidity was computed using equation 4.

**Exergy at Inlet**

$$\left(1 - \frac{T_{room}}{T_{solar}}\right) Q_{rad} + M_{1\ wat}[(h_1 - h_o) - T_o(s_1 - s_o)] + M_{1\ dry}[(h_1 - h_o) - T_o(s_1 - s_o)]$$

Eqn. (3 a)

**Exergy at Outlet**

$$M_{2\ wat.vap}[(h_2 - h_o) - T_o(s_2 - s_o)] + M_{2\ dry}[(h_2 - h_o) - T_o(s_2 - s_o)] + T_oS_{gen}$$

Eqn. (3 b)

Applying steady state condition

$$T_oS_{gen} = \left[ \left(1 - \frac{T_{room}}{T_{solar}}\right) Q_{rad} + M_{wat}[(h_1 - h_2) - T_o(s_1 - s_2)] + M_{dry}Cp_{dry}[(T_1 - T_2) + T_o \ln \ln \frac{T_1}{T_2}] \right]$$

Eqn. (4)

**Energy and Exergy analysis on Algae Combustor**

With the assumption of complete combustion with no ash formation and applying steady state energy equations on an algae combustion, the exergy loss in

combusting dry algae feedstock was computed using equations 5a and 5b. Hence, exergy balance provides insight on the amount of work loss which can be utilized as useful work if there was no entropy generation (reversible work).

**Applying steady state equation**

**Exergy At inlet**

$$\left(1 - \frac{T_1}{T_{1444}}\right) Q_{com} + M_{1\ wat}[(h_1 - h_o) - T_o(s_1 - s_o)] + M_{1\ dry}[(h_1 - h_o) - T_o(s_1 - s_o)]$$

Eqn. (5a)

**Exergy at outlet**

$$M_{2\ wat.vap}[(h_2 - h_o) - T_o(s_2 - s_o)] + M_{2\ dry}[(h_2 - h_o) - T_o(s_2 - s_o)] + T_oS_{gen}$$

Eqn. (5b)

$$T_oS_{gen} = \left[ \left(1 - \frac{T_{rm}}{T_{1444}}\right) Q_{comb} + M_{wat}[(h_1 - h_2) - T_o(s_1 - s_2)] + M_{dry}Cp[(T_1 - T_2) + T_o \ln \ln \frac{T_1}{T_2}] \right]$$

Eqn. (6)

**ENERGY AND EXERGY ANALYSIS ON ALGAE GASIFIER**

**Energy Balance**

Applying steady state conditions in respect to energy and mass transfers on the following assumptions:

- I. Product gas mixture has high concentrations of carbon monoxide and hydrogen gases than other gases.
- II. Gasification begins at a temperature of 1000 °C

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From the above assumptions, energy equations for final exit temperature of produced gas and energy balance on algae gasification are shown in equations 7-8, while exergy loss in gasification of algae feedstock was computed using equation 12.

$$Q_{in} + (M_{wet\ feed.st} h_1 + M_{air} \times h_1) = (M_{gases} \times h_2 + M_{wat.vap} \times h_2) \quad \text{Eqn. (7)}$$

$$T_{2\ exit} = \frac{[Q_{in} + M_{dry\ feed} \times C_{p_{dry\ feed}} \times T_1 + M_{wat}(h_1 - h_2) + M_{air} \times h_1]}{M_{gases} \times C_{p_{gases}}} \quad \text{Eqn. (8)}$$

### Exegetic Balance

Exergy at Inlet

$$\left(1 - \frac{T_1}{T_2}\right) Q_{in} + M_{wat}[(h_1 - h_o) - T_o(s_1 - s_o)] + M_{dry}[(h_1 - h_o) - T_o(s_1 - s_o)] + M_{air}[(h_1 - h_o) - T_o(s_1 - s_o)] \quad \text{Eqn. (9)}$$

Exergy outlet

$$M_{gases}[(h_2 - h_o) - T_o(s_2 - s_o)] + M_{watvap}[(h_2 - h_o) - T_o(s_2 - s_o)] + T_o S_{gen} \quad \text{Eqn. (10)}$$

Collecting like terms

$$T_o S_{gen} = \left[ \left(1 - \frac{T_1}{T_2}\right) Q_{in} + M_{wat}[(h_1 - h_2) - T_o(s_1 - s_2)] + M_{dry}[(h_1 - h_o) - T_o(s_1 - s_o)] + M_{air}[(h_1 - h_o) - T_o(s_1 - s_o)] - M_{gass} [(h_2 - h_o) - T_o(s_2 - s_o)] \right] \quad \text{Eqn. (11)}$$

$$T_o S_{gen} = \left[ \left(1 - \frac{T_1}{T_2}\right) Q_{in} + M_{wat}[(h_1 - h_2) - T_o(s_1 - s_2)] + M_{dry} C_{p_{dry}} \left[ (T_1 - T_o) - T_o \ln \ln \frac{T_1}{T_o} \right] + M_{air} C_{p_{air}} \left[ (T_1 - T_o) - T_o \ln \ln \frac{T_1}{T_o} \right] - M_{gas} C_{p_{gas}} \left[ (T_2 - T_o) - T_o \ln \ln \frac{T_2}{T_o} \right] \right] \quad \text{Eqn. (12)}$$

## RESULTS AND DISCUSSIONS

### Energy and Exergy Balance on Solar Dryer

The amount of radiant energy required to completely dry wet algae feedstock with moisture content range of 10% to 50% is illustrated in Figure 2. As seen in Figure 2, the energy required increase with rise in water level. Expectedly, the entropy increase with rise in energy utilization at each water level. Exergy loss at 10 to 20% humidity was observed to be lower compared to exergy loss between 40 and 50% humidity. These increments represent increase in energy capital costs.

Increases in both energy input and exergy loss indicate associated loss in efficiency when using a solar dryer to dry wet feedstock also it indicate the increasing complexity of energy utilization towards optimizing synthetic gas production via gasification. However, the exergy values could be lower compared to other means of drying like combustion drying.

### Drying Space per Unit Mass

It was observed that 50% humidity require the highest drying space despite having the same amount of dry feedstock

with other humidity levels; this requirement is largely attributed to large water contained as shown in figure 3. 33.3% rise in drying space requirement between 20% and 30% humidity and 50% increase

between 40% and 50% humidity were observed. This increase in drying space was brought about by increase water which will have significant cost implication in energy provision.

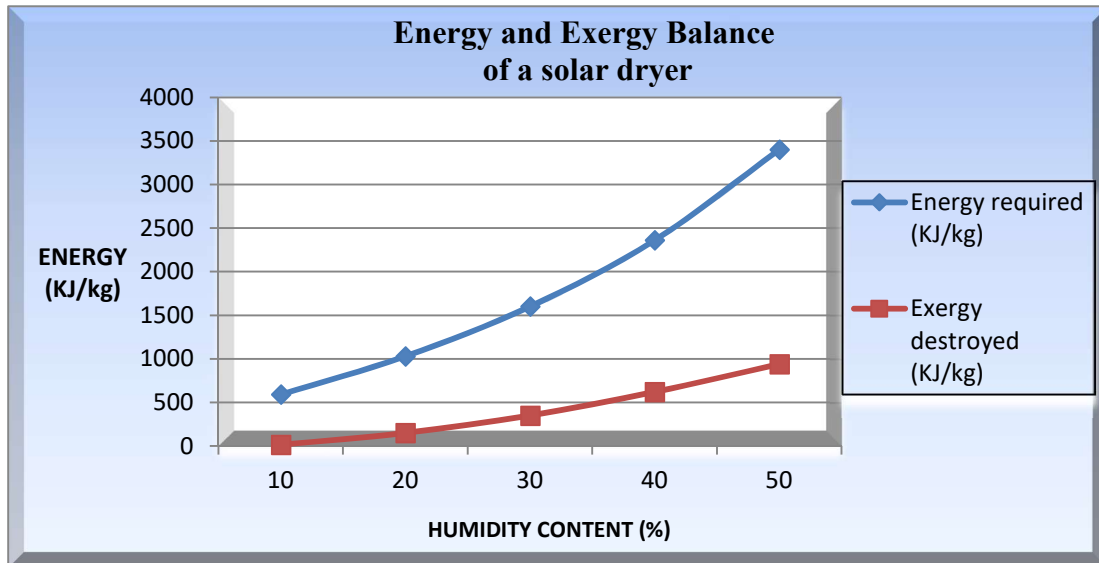


Figure-2: Energy and Exergy Balance of a Solar Dryer

#### Energy and Exergy Balance on Algae Combustor

Exergy losses in a solar dryer were compared to exergy losses in combustion to dry wet feedstock with result illustrated in figure 4. With fixed energy demand for drying, the exergy loss linearly increased as the humidity increased: 50% humidity level recorded highest useful work loss due to its high intake (equations 3a and 3b). The increase in entropy generation is caused by the loss of chemical exergy of the feedstock due to high temperature of combustion (1444K). It was observed that exergy loss values recorded in using radiant heat from

the sun were smaller compared to combustion drying. Figure 4 shows clearly the strong potential of substituting combustion drying with solar dryer which is the objective of this study. This further suggests there will be excess of energy supplied when using combustion to dry feedstock, consequently this excess energy can destroy the feedstock. Substituting combustion drying with solar drying will make more energy available for more energy consuming processes like devolatilization (pyrolysis) and gasification which both require 1.5MJ and 10.1 MJ per kilogram of dry feedstock respectively.



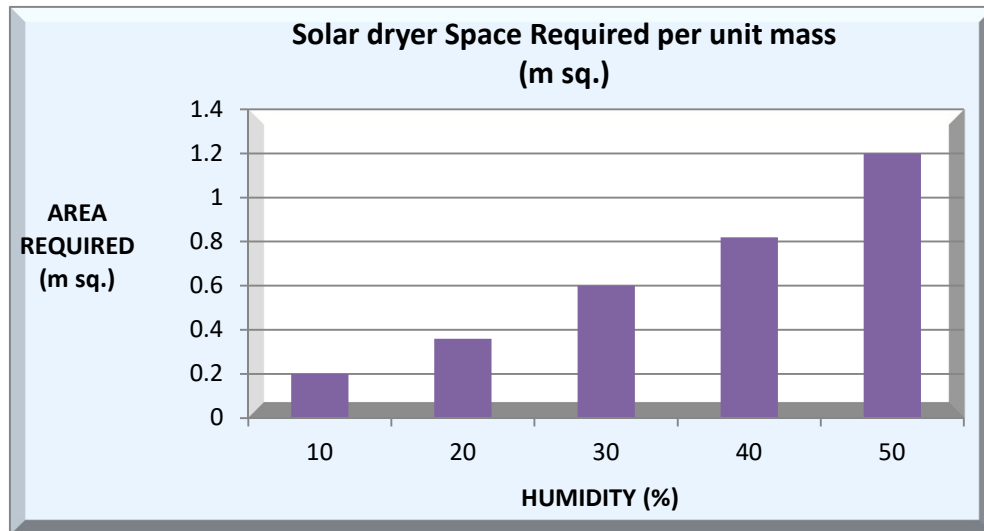


Figure-3: Drying space requirement per unit mass

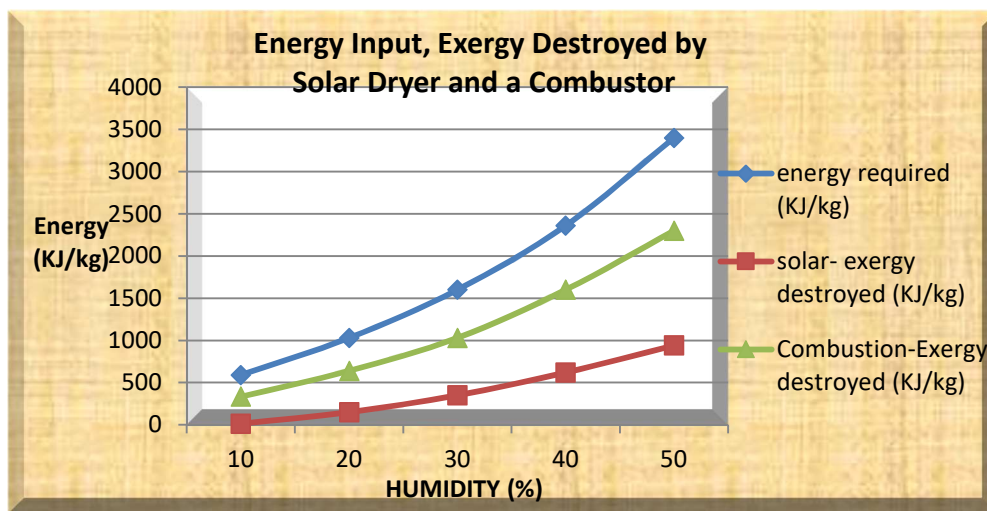


Figure-4: Energy input and Exergy loss in a Solar Dryer and a Combustor

#### Energy and Exergy Balance on Microalgae Gasification Chamber

Exit temperature profile of produced gas was computed using equation 8 and the exit temperature profile presented in Figure 5. It was observed that water presence in the feedstock had negligible effect on exit temperature. This observation suggests that the water

trapped must have been evaporated before pyrolysis and gasification reactions. Several studies indicate that water content, amount of air (oxygen or steam), nature of feedstock and feedstock delivery pattern have all have significant impact on the final composition of product gas in gasification. However, from this numerical research, water content was observed to have

negligible impact on the exit temperature of product gas but it could impact the final

concentration and quality of product gases.

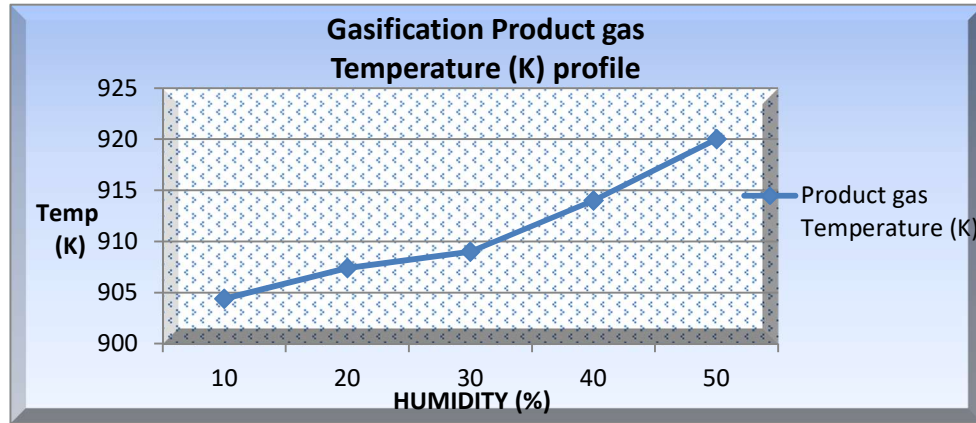


Figure-5: Product gas Temperature Profile

Exegetic balance was conducted on the assumption of complete combustion with no ash consideration and the gasifier insulated (no heat loss). The exergy loss profile from ideal algae gasifier is illustrated in Figure 6. At every humidity level, the entropy values during gasification were observed to be higher than values recorded in solar dryer and combustion as seen in Table 2. Due to high entropy generated by gasification, the efficiency is impacted by its

high energy demand. Gasification is an endothermic process requiring high energy input from energy source, the high energy intake leads to substantial destruction of useful work (entropy). The marked difference in the entropy values was because of the high energy intake of the two endothermic processes (pyrolysis and gasification) each requiring mega joules of heat.

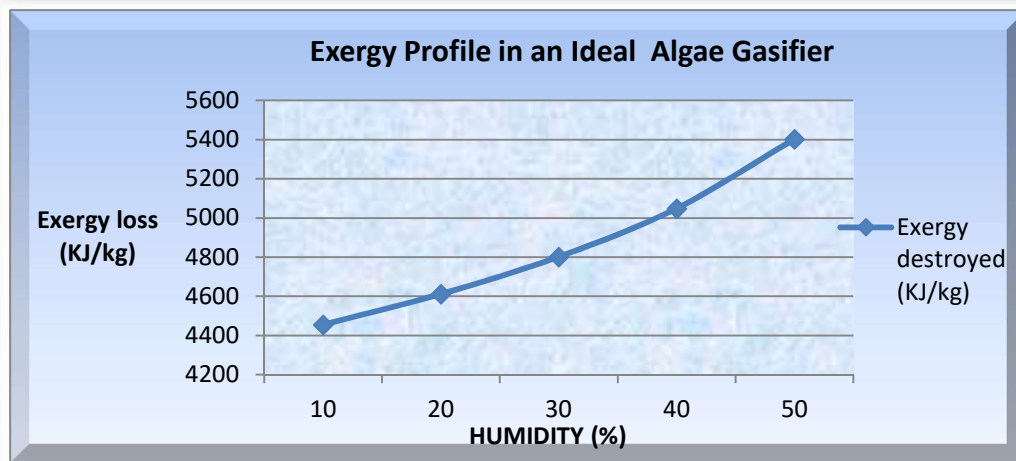


Figure-6: Exergy loss profile in an algae gasifier





**Table 2:** Exergy losses in Gasification, Combustion and Solar dryer

Humidity Level (%)	Gasification Exergy loss (KJ/kg)	Combustion Exergy Loss (KJ/kg)	Solar Dryer Exergy loss KJ/kg)
50	5402	3080	940
40	5049	1600	620
30	4802	1030	350
20	4612	640	150
10	4455	333	14

## CONCLUSION

Biomass conversion is a complex process, the thermodynamics analyses are based on chemical steady condition that provide basic kinematic information of biomass gasification. The exergy values recorded in solar drying were much lesser than in combustion drying; indicating that entropy generation is lower in solar drying than in a combustion drying. The integration of a solar dryer minimizes the phenomenon of destroying useful work due to irreversibilities in algae gasification process. With exit gas temperature of 1444K, the gasifier is the least energy efficient component in entire microalgae gasification process due to its high energy demand leading to destruction of useful work. The high energy input of the gasifier chamber indicates high capital costs and degree of complexity in commercial production of synthetic gas through gasification. Exergy analyses reveal useful design information in evaluating the behaviour of microalgae biomass gasification system.

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