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Spring 2015

Emission and energy analysis of self-sufficient biomass power plant to achieve near net zero CO$_2$ emission

Baburaj Kanagarajan

Recommended Citation

EMISSION AND ENERGY ANALYSIS OF SELF-SUFFICIENT BIOMASS POWER

PLANT TO ACHIEVE NEAR NET ZERO CO$_2$ EMISSION

by

BABURAJ KANAGARAJAN

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

2015

Approved by

Dr. Steven Corns, Advisor
Dr. Kelly Homan
Dr. Glenn Morrison

ABSTRACT

The use of biomass to fuel power plants is considered by many to be a carbon neutral solution to carbon dioxide emissions. One objection to this method of power generation is the gasoline or diesel spent in the transportation and feedstock production, which is a major contributor to carbon emission. In addition, costs associated with the transportation of the biomass fuels are also a major limiting. This work investigates the use of a hybrid farming facility as a means of distributed generation combined. A model that incorporates a small scale biomass power facility located within a farming facility is examined. By locating the power facility at the center of the facility and having the biomass crop fields surrounding the power plant, transportation costs for power generation are greatly reduced. In addition, the use of electric powered farm equipment for sowing seeds, harvesting, and fertilizer application reduces fossil fuel consumption to near zero. Powering these vehicles with the electrical energy from the power plant on site allows for a self-sufficient agricultural facility with near zero emissions.

ACKNOWLEDGMENTS

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1. INTRODUCTION

This work presents a feasibility study of a self-sufficient farming facility that produces the power with near net zero CO_2 emission which can be used to power the farm facility and excess power being sent to grid without affecting the food production. The proposed method incorporates local, distributed generation and the use of biomass crop residue as a fuel to generate electricity which in turn is used to power the vehicles used for farm, house loads, and transportation vehicles. As only the crop residue is used as fuel for power generation the food production is not affected. The excess power generated is sent to the grid for the local community. There are two areas where improvements would be realized from this facility: net zero CO_2 emissions and energy self-sufficiency.

There are many biomass power plants with dedicated energy crops such as poplar, wood etc. as the source of fuel. If a significant number of farmers switch from food crop production to these dedicated energy crops it would lead to decline in the food production. This could pose a food security threat, making biomass a less-attractive fuel for the power production. If food crop residue is used for the biomass power production, farmers can also get income through food making the power production cost cheaper. This study discusses the feasibility of the power production with the residue of the food crop as a biomass fuel and does so without a reduction in food production.

1.1 NET ZERO CO$_2$ EMISSION

After the industrialization of agriculture, crop production has been dominated by the fossil-fueled tractor. When investigating the use of a biomass fuel, the biomass material must be transported to the power production facility from the farm. This again is currently done using fossil fueled vehicles. Thus both the crop production and the transportation or biomass feedstock add CO$_2$ to the environment which cannot be accounted for in the absorption of CO$_2$ by the biomass crops via photosynthesis (Figure. 1.1). This raises the question as to whether a net zero CO$_2$ emission facility is feasible.

One solution that has been explored is the use of biomass fuel. Biomass is a renewable resource and considered to be CO$_2$ neutral as the CO$_2$ released during combustion will be re-captured by the regrowth of the biomass through photosynthesis (Linghong Zhanga, Xub and Champagnea 2010). When biomass is fully burned, the amount of carbon dioxide produced is equal to the amount which was taken from the atmosphere during the growing stage. Therefore, no net addition of CO$_2$ to the atmosphere occurs and unburned biomass can be regarded as a carbon sink. This is known as the carbon cycle or zero carbon emissions (Figure 1.2).

The elimination of the vehicles is not practical in the current scenario, as modern farming requires a large amount of work supported by these vehicles. However, one possibility would be switching these vehicles from fossil fuel to a renewable fuel. This study focuses on the use of biomass, which would provide two options:

1) Bio fueled vehicle

2) Electrical powered vehicle

Figure 1.1 Current biomass power plant facility

Net CO_2 emission > zero

CO_2 emission

Biomass Fuel

Biomass Crop Production

Transportation

Power Production

Net CO2 emission zero

CO2 emission

Biomass Crop
Production

Biomass Fuel

Power Production
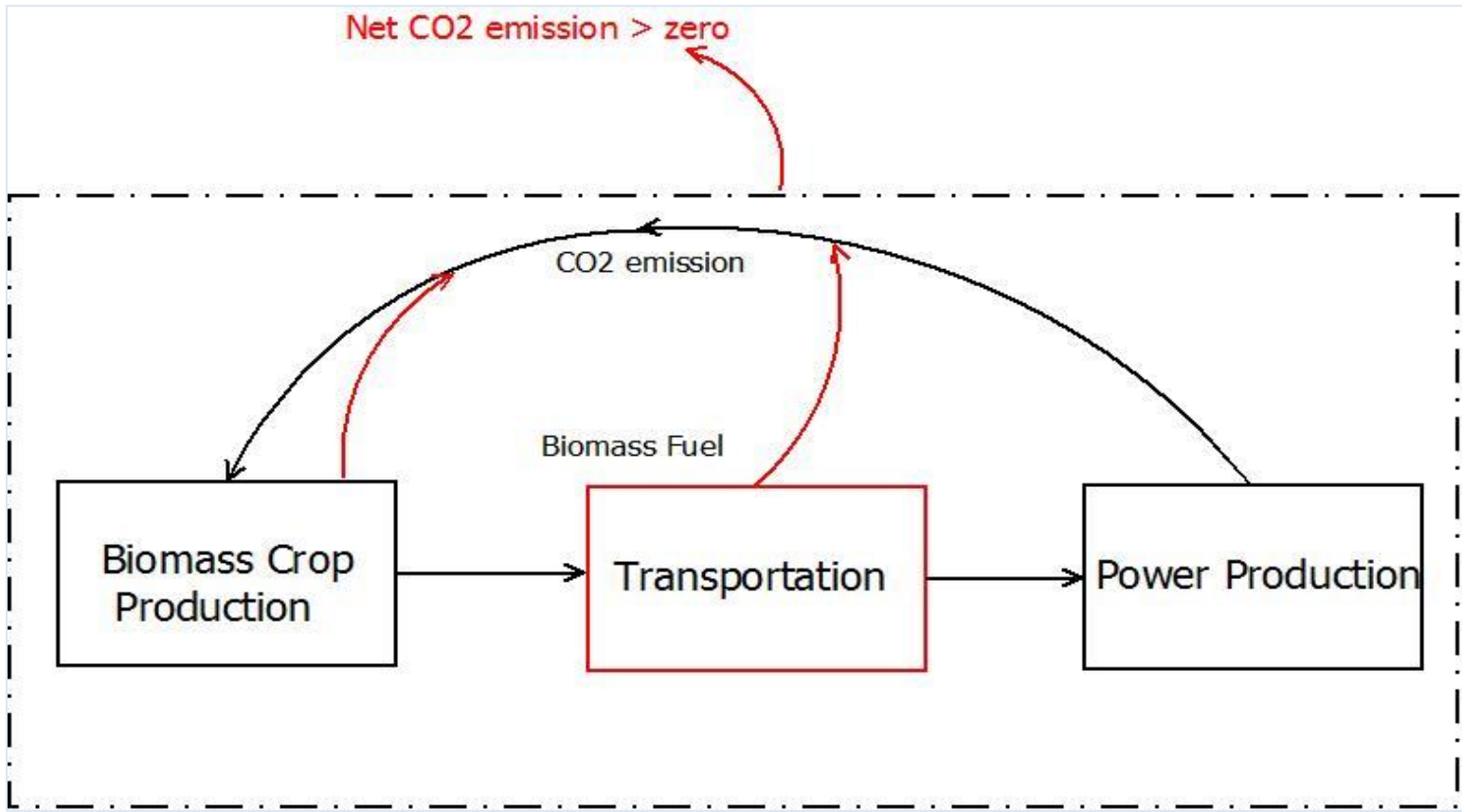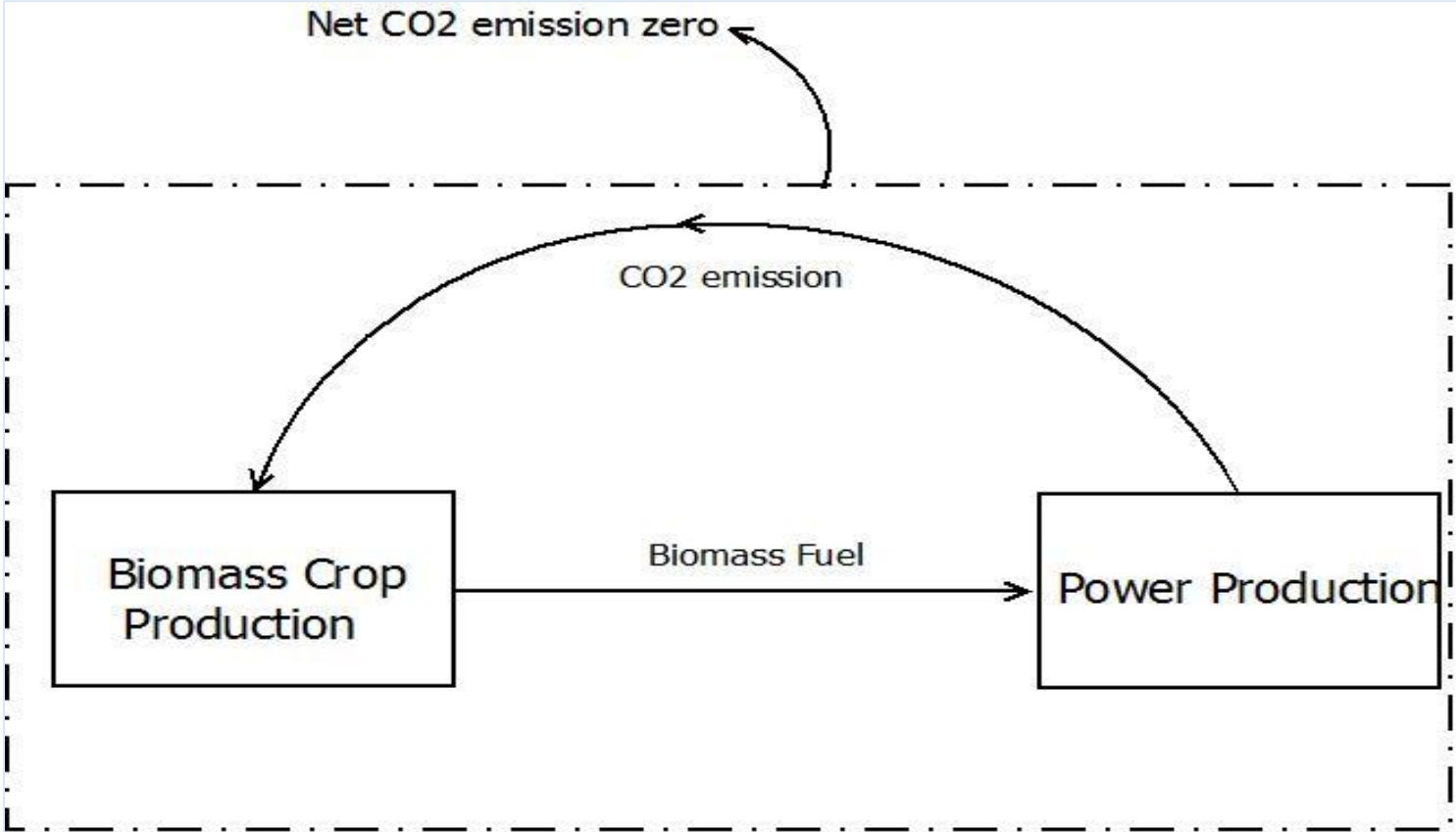
Figure 1.2 Carbon cycle for Zero CO_2 emission

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This study deals with the production of electricity for use at other locations on the facility, and so leaves the use of installing bio-fuel production capabilities at these facilities for future work.

1.2 ENERGY SELF SUFFICIENCY

Power is produced by the biomass power plant and used within the agricultural facility for farm operations, transportation, and residential uses. The fuel for the power plant is produced from the facility. Thus this facility produces the energy it consumes, making it self-sufficient energy facility (Figure 1.3).

Transportation costs are also a major contributing factor in energy usage. The energy density of the crop residue biomass is significantly lower than fossil fuels, so the volume that must be transported is higher for the same energy production. This makes the transportation cost of the crop residue biomass fuel from the fields to the power production facility fairly high. In this study, the biomass power plant is located at the center of the farm. Because of the decreased distance the fuel must be moved, the energy consumption due to transportation would be lower, leading to the lower transportation cost. In addition, the use of only electrical energy will allow for any excess electricity generated to be sold on the grid (Figure 1.3). This excess power can be used by the local community making it as an attractive option for rural electrification

Figure 1.3 Overall Layout
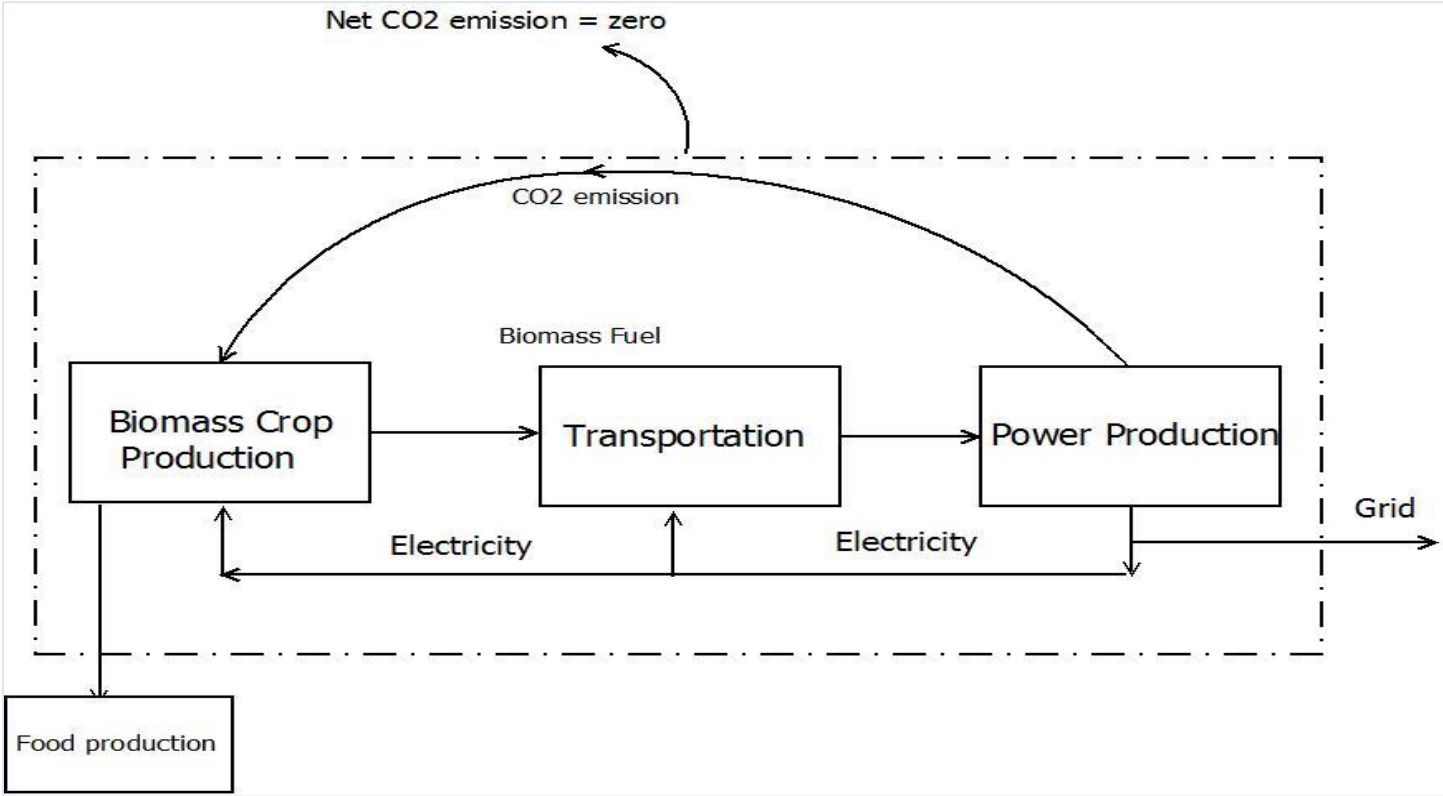
2. MOTIVATION

In most parts of the world, electricity is generated from the large thermal power plants, stepped up to high voltage to avoid transmission losses, and sent to end users through a centralized grid. This centralized electricity generation and grid system scheme has total losses of 65% of the primary energy input (Department of Trade and Industry 2006). One solution to reduce these losses is to have many small scale power generating stations in the place of large power generating stations and placing them near the point of use. This is termed as a decentralized or micro electricity generation and grid system. It can be disconnected from the central grid and operate autonomously using its own control capability. By placing the energy in a decentralized manner, less energy needs to be transferred via the transmission grid, helping to avoid grid overloading .The efficiency can be further increased by utilizing some of the rejected heat from the plant for water and space heating. This technology is called combined heat and power (CHP).

Although electricity has now become a need for the people, some of the human population around the world does not have access to it. The main victims are the rural communities in less developed countries. They are excluded from the centralized grid due to their geographical locations. In most of the rural areas, the population is also smaller, with agriculture the primary source of income. Thus the electricity demand would be spread across larger distances making the cost of electricity higher in rural areas. However, renewable energy resources like wind, solar, biomass are available in large amounts in these areas. By utilizing these resources for the electricity generation combined with technologies like micro generation and micro grids, CHP, the rural electrification can be made possible, affordable and also with less carbon emissions.

2.1 OBJECTIVES

There are three objectives to this evaluation of a self-sufficient facility. They are to examine:

1) The feasibility of an agricultural facility capable of generating sufficient biomass to meet its energy needs by analyzing energy content and composition of the crop that suits the power production.

2) Through energy analysis that the power generated will support electric vehicles used for crop production and transportation and the electricity used for house loads.

3) Through an emission analysis that the power production will have near net zero CO_2 emission.

The objective of this study is to compare the results of these analyses to the existing body of knowledge to validate the results.

Firstly, a biomass crop rotation sequence is chosen. Then an energy content and composition are obtained by performing the ultimate analysis and the calorific values of the biomass fuel. These values can be obtained from the biomass database (ECN 2013). An energy analysis was performed on the farm, transportation vehicles, and the house loads. These values can be obtained by knowing the different farm operations involved and the energy consumed by different equipment used in power production (Baky, et al. 2006)

As vehicles used in farm operations and the transportation are all electric powered the only source of emission is the power production. The emissions analysis is performed

on the power plant by determining the composition of the flue gas emitted through gasification and combustion reactions.

2.2 ASSUMPTIONS

1) For this analysis, it is assumed that all of the crop residues are used as the fuel for the power production. Seedling production is not included in this study (Craig and Mann 1996). While it is a common farm practice for some of the crop residues and green manures to be left in the field to add nutrients to the soil, we are assuming this amount is negligible (Craig and Mann 1996).

2) Transmission and heat loss are not considered in this study.

3) The CO_2 emitted during the construction of facility, manufacture of transportation and farm equipment, and other manufacturing associated with the facility is considered outside the scope of this study.

To improve the overall performance of the facility, organic farming methods are considered. This includes investigating how to reduce the NOx emission by fertilizer. The organic farming problems that must be addressed are: 1) weed and pest control, 2) adding the nutrients to the soil, and 3) Soil erosion. These can be achieved through crop rotation. The crop rotation sequence should be known to find out the feasibility of the biomass fuel used for the power production without affecting the food production. As a common farm practice some of the crop residues and green manures are left in the field for adding nutrients to the soil. For this study, it is assumed that all of the crop residues are used as fuel for power production. In addition, seedling production is not included in this study.

If the crop rotation sequence is known, it is possible to know the different farm operations like mowing, sowing etc. It is then possible to calculate the energy consumed

by the farm vehicles. The energy consumed by the different equipment used in power production, transportation, and operations can be found by evaluating the ratings of the equipment. Once the power generated and consumed is determined, the excess power sent to the grid can be calculated by subtracting the all farm facility energy from the total power produced

The emissions from the facility should also be calculated. As the transportation and farm operations are all done by electric powered vehicles, the power production is the only source of the emission. With biomass used as the only fuel for the power production, net zero CO_2 emission can be achieved in the facility.

3. BACKGROUND

The electricity production in the world is mainly dependent on fossil fuel such as coal, natural gas, and oil. However, these sources are viewed by many as unsustainable, as future electricity demand is affected by the limitation of fossil fuel reserves and the environmental impact of emissions from fossil fuel combustion (Lior 2010). In addition, the Intergovernmental Panel on Climate Change (IPCC) reported that continued emissions from sources such as these fuels will lead to a temperature increase of between 1.4°C and 5.81°C over the period from 1990 to 2100 (Mahmoud, Shuhaimi and Samed 2009). The accelerated increase in temperature rise is greater than the estimated maximum average temperature increase that the environment can withstand (Watson and Team 2001). Thus the world is shifting towards renewable resources such as wind, solar, and biomass for energy production.

Biomass is widely used as a renewable energy resource in the United States. However, most commercially used biomass resources are not sustainable. For example, wood is one of the commonly used biomass fuel, but consuming larger quantities of trees will lead to deforestation. The use of edible biomass crops like oil seeds, corn, soy beans for fuel could raise food prices, as could dedicated fuel crops. Maximizing the use of crop residues from food crops for biomass energy can help solve this problem.

Another issue with current agricultural practices is CO_2 emissions. The obvious source is from the vehicles using fossil fuels. However, modern farming also uses electricity in day to day operations use electricity, a majority of which is produced in fossil fuel power plants. In addition, the fertilizers used for growing these crops not only

pollute the land but also emit carbon. This issue can be solved by raising the crops with organic farming techniques.

Biomass is a considered by many to be CO_2 neutral, as the CO_2 released during combustion will be re-captured by the regrowth of the biomass through photosynthesis (Linghong Zhanga, Xub and Champagnea 2010). When biomass is fully burned, the amount of carbon dioxide released is equal to the amount which was taken from the atmosphere during the growing stage, so there is no net addition of CO_2 to the atmosphere. This is known as the carbon cycle or zero carbon emissions.

Feedstock production is another source of CO_2 emission which has to be taken in to consideration. The energy supplied to the farming system was of renewable origin until the mechanization of agriculture. Currently, agriculture is mainly dependent on the tractor fueled by diesel fuel, one of the widely used fossil fuels. Huge amounts of energy are consumed in agricultural sector and are responsible for 14% of total global greenhouse gas (GHG) emissions (Ahlgren, et al. 2009).

Of the 3 systems (feedstock production, transportation, electricity production) (Figure 1.3) considered in the life cycle assessment (LCA) of biomass gasification, biomass feedstock production accounts for 77% of non-power plant system energy consumption and 62% CO_2 emissions (Mann and Spath 1997). These emissions can be reduced in two ways:

1)   By having the power plant located at the center of the farm-This reduces emission due to the biomass fuel transportation.

2)   By using the renewable fuel for the equipment used for feedstock production.

One of the feasible renewable fuels for the farm equipment is bio-based fuel. There are studies on self-sufficiency of the farm based on bio-fuels like rape methyl ester (RME), ethanol and biogas (Hansson, et al. 2007). The study on self-sufficient farm using fuel cell tractor with bio-fuel Salix, ley and straw had already been conducted (Ahlgren, et al. 2009). In this study, the tractors are electrically powered and the electricity is produced by using biomass grown in the farm. Thus the farm is self-sufficient in terms of fuel.

The use of battery powered tractors has previously been investigated (Mousazadeh, et al. 2011). In this study, battery powered tractors were considered for a wide range of light duty operations. By way of comparison, the capacity of the John Deere 5M series model engine currently used for a full range of farm operations ranges from 75-115hp (John deere 2013). This is comparable in power output to a Nissan Leaf electric vehicle, which has a motor capacity of 107hp (Nissan USA 2013). This shows that the electric powered tractor could also be used for heavy duty operations. When compared to Fuel Cell Electric Vehicle Battery (FCEV), Battery powered electric vehicle (BPEV) performs far more favorably in terms of cost, energy efficiency, weight and volume. It is believed that these differences will be very high when the energy is derived from renewable resources (Eaves and Eaves 2004). The biomass is a renewable energy and hence in this study the battery powered tractors are used for farm operations to gain the above advantages.

In the proposed farm, the output from the biomass farm is considered to be both the food and agricultural residues. This reduces the power production cost. The emission

and energy produced depends on the biomass crop. It is well known fact that the crop rotation adds nutrients, controls pest and soil erosion (Hansson, et al. 2007).

The use of biomass for power generation with decreased carbon emission has been previously studied. 95% carbon closure was achieved in research conducted on the Biomass Integrated Gasification Combined Cycle (BIGCC) (Mann and Spath 1997). In Mann and Spath's case, diesel fuel was used for the farm operations and the biomass power plant was operated using a Brayton cycle gas turbine. In this study, part of the electricity was used to power agriculture tractors and the biomass feedstock transport trucks with the excess electricity sent to the grid. Thus the only source of CO_2 emission is from the combustion of biomass feedstock. Since the emitted CO_2 is absorbed by the growing of biomass crops on the farm, this results in near net zero CO_2 emission. The main resource for the electricity production is the biomass fuel and since the power plant is located in the farm, the results in a facility which is self-sufficient when energy is considered.

The power produced from the biomass can be used to power rural areas by micro grid. There are fewer transmission power losses from the micro grids compared to central grid. As the rural areas have high amount of biomass resources, biomass power micro grid is feasible in rural areas. The system would be more economical if cooperative method of farming is adapted.

4. BIOMASS

Biomass is a biological material derived from living, or recently living organisms. In the context of biomass for energy this is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material (Biomass Energy Centre 2008). This material is attractive because it is naturally occurring and sustainable in that it does not require mining and will replenish given a sufficient length of time.

4.1 CLASSIFICATION OF BIOMASS CROPS

When considering a biomass energy facility, identification of the biomass to be used is a crucial first step. For this project, the use of biomass energy crops was selected for consideration. There are three types of biomass energy crops (Srirangan, et al. 2012):

1) First-generation feedstock is edible feedstock from the agricultural sector such as corn, wheat, sugarcane, and oilseeds. Though the use of edible feedstock content may potentially enhance the conversion and yield of biofuels from biomass, it tends to impact food prices (Francesco 2010).

2) Second-generation feedstock is non-edible and comprise of raw materials derived from lignocellulose biomass and crop waste residues from various agricultural and forestry processes. These raw materials are one of the best options available for fuel production since their utilization will not impact the food industry.

3) Third-generation feedstock is a wide collection of fermentative and photosynthetic bacteria and algae which are currently being explored for fuel usage, as biocatalysts have high oil/lipid, carbohydrate, or protein contents.

Though in comparison to the first- and second- generation feedstock, microbial cells can be obtained in high yields via bioreactors with no requirement of arable crop lands and other farming inputs like fertilizers, water, and pesticides (Nigam and Singh 2011), they are still technologically immature.

As the goals of this research are to show the feasibility of an agricultural facility to provide for its own energy needs while still producing food, second generation energy crops were selected for this work. These crops can be broadly categorized in to two major groups: Organic waste residues and dedicated energy crops.

4.1.1 Organic Waste Residues. Crop residues are lignocelluloses feedstock derived from agricultural processes include corn cobs, corn stover, wheat straw, rice hulls, and cane bagasse. Arable farms have a readily available, locally produced, and recyclable resource for energy generation in the form of different types of production residues. These residual products can be used today for the production of heat, electricity and vehicle fuel. The energy potential of these residues is high due to its availability and its high carbohydrate content. The agricultural sector in Western Europe and in the US is producing food surpluses, making the residues (non-edible) from the agricultural land a more economical option for energy production. Demand for energy will provide an almost infinite market for energy crops grown on such surplus land, though it should be noted that the energy content of residues varies from crop to crop. The woody feedstock is seen as an attractive because of their high cellulose and low hemicelluloses composition. The increasing use of woody biomass in the saw mill, pulp and paper industries and heating sector are increasing the wood price (Uslu, Gomez and Belda

2010). Considering the future of biomass crops, non-wood biomass fuels are taken in to consideration.

4.1.2 Dedicated Energy Crops. These are exclusive energy crops from the lignocellulose feedstock for generating energy to meet the increasing energy demand. Advantages of energy crops are: fast growth rate, fecundity, high tolerance to various environmental stresses, high energy content, short rotation and relative ease of cultivation in comparison to grain crops. Some of the crops used as dedicated energy crops include: perennial grasses like switch grass and Miscanthus and woody energy crops like poplars, willows, and eucalyptus (Klass 1988) (Srirangan, et al. 2012).

4.2 FEEDSTOCK PRODUCTION

In this study, biomass fuel is the primary resource for the power production. Under current practices, biomass feedstock production, storage, and transportation with farm equipment lead to combustion of fossil fuel and use of energy from alternate sources, which also emit CO_2 and other greenhouse gases (GHGs) into the atmosphere. The technical development of systems for energy generation based on biomass has progressed rapidly over the last few years and the number of small-scale applications suitable for farm use has increased. The production of biomass-based energy carriers can have issues such as changed land use and decreased food production, which are making biomass a constrained resource (Kløverpris 2008). As biomass is a bulky material, it occupies more volume during transportation, limiting the economically feasible transport distance. Also it needs energy for growth, harvest, and conversion to useful energy

carriers. These issues can be avoided if the biomass is only used on the farm of origin and only the residual (non-edible) products are used as energy sources.

The systems investigated include cultivation and handling of the amount of agricultural products needed to produce motor fuel for the entire crop rotation and growing seasons. The agricultural residues produced are used to produce electricity, which is utilized in field operations for the entire farm field. The system considered here includes the whole life cycle, including transport, for the products used within the system. Production of capital goods such as machinery and buildings for cultivation and fuel production was not included in the study, as the production of capital goods is of minor importance for the overall result (Bernesson, Nilsson and Hansson 2004).

4.3 CROP ROTATION

To avoid the emission of NO_x, SO_x and other pollutants from compounds absorbed from the soil, organic farming practices are assumed to be used on the farm i.e. synthetic pesticides and fertilizers are not used. Only non-nitrogen mineral fertilizers like gypsum and calcareous amendments are allowed to be used in organic farming. Cover crops and sophisticated crop rotations are used to modify field ecology, effectively disrupting habitats for weeds, insects, and disease organisms. Mechanical tillage and hand-weeding are also used to control weeds. The soils are fertilized by manure, compost and by using suitable crop rotations. The problem with the crop rotation is that each of the crops in the crop sequence in an organic farming system is affected by the cultivation of the other crops. One crop may influence the yield of other crops in the rotation through positive preceding crop effects or influences on diseases. The methods for allocation of

processes affecting other crops in a positive way in cropping plan are already been developed (Zeijtsa, Leneman and Sleeswijk 1999). According to those methods, the environmental impact of green manure should be allocated to all crops according to land use per crop in the cropping plan, as organic matter benefits all crops. For leguminous cash crops, it can be assumed that only the specific crop profits from the nitrogen binding.

5. METHODOLOGY

The facility proposed here includes the feedstock production, transportation, and electrical power generation (Figure 1.3). The electricity produced would be used to power the farm and transportation vehicles. The excess electricity is sent to the grid for local community consumption. The amount of electricity that can be sent to the grid can be calculated using the electricity consumption of electric vehicles and the house loads. To accomplish this, an energy analysis was performed for all the components of the facility. In addition to the energy analysis, an emission analysis was performed for the power plant to demonstrate that the net CO_2 emission is zero.

5.1 FEEDSTOCK PRODUCTION

The number of field operations and yields are presented in Table 5.1. These values are average data from Logarden research farm (Baky, et al. 2006) located in south-western Sweden (58^0 20'E). Table 5.1 gives the optimized seven-year crop rotation to prevent problems with pests and weeds and to be favorable from an economic prospective. Nitrogen is supplied by nitrogen-fixing crops grown twice in the rotation. The biomass is assumed to be grown in total area of 2000 ha. For this study it is assumed that the crops listed in Table 5.1 are reported to be grown in Minnesota, USA (University of Minnesota Extension 2013). Rye and oats (Daniel E. Kaiser, et al. 2011), Winter Wheat (Wiersma, et al. 2012), Rapeseed (MacKensie, Green Manure Cover Crops For Minnesota 2008), Field beans (University of Minnesota 2013) can be grown in state of Minnesota, USA. Alfalfa can be used as green manure (MacKensie, Green manure cover crops for Minnesota 2008). In this study alfalfa is used as green manure. The straw to

grain ratio is assumed to be 0.85 to 0.95 depending on the crops (Nilsson 1999). As there

is no grain produced by alfalfa, the grain yield is assumed to be equal to straw yield.

Table 5.1 Crop rotation, grain and straw yields for the farm studied

Crop rotation	Grain Yield (kg ha^{-1} year^{-1})	Straw Yield (kg ha^{-1} year^{-1})
Field beans	2400	2040
Oats	3200	2720
Green manure/alfalfa	6000	6000
Winter rapeseed	2000	1700
Winter wheat	3500	2975
Green manure/alfalfa	6000	6000
Rye	3200	2720

5.2 POWER PRODUCTION

The power plant layout is shown in Figure 5.1. The syngas production, heat exchanger and the ceramic candle filter set up shown in the Figure 5.1 is based on the system developed by Institute of Gas Technology (IGT) (Craig and Mann 1996). The syngas is combusted in the combustion chamber by following the Brayton cycle. The flue gas from the turbine is used to dry the biomass and reduce it to 20% moisture content. Some of the heat carried by the syngas is also used for the house load heating. The biomass fuel used is assumed to have 20% moisture and their properties are given in Table 5.2. The empirical formula of the fuel will be $CH_xO_yN_z$ neglecting the other elements.

5.2.1 Gasifier. Gasification is the conversion of solid or liquid feedstock into useful and convenient gaseous fuel or chemical feedstock that can be burned to release energy or used for production of value-added chemicals (Basu 2010). Gasification and combustion are two closely related thermochemical processes, but there is an important difference between them. Gasification packs energy into chemical bonds in the product gas, combustion breaks those bonds to release the energy. The gasification process adds hydrogen to and strips carbon away from the feedstock to produce gases with higher hydrogen-to carbon (H/C) ratio, while combustion oxidizes the hydrogen and carbon into water and carbon dioxide, respectively. Gasification typically requires a medium like steam, air, or oxygen to convert solid feedstock in to gas. Air is used as the medium for this study as it is easily available.
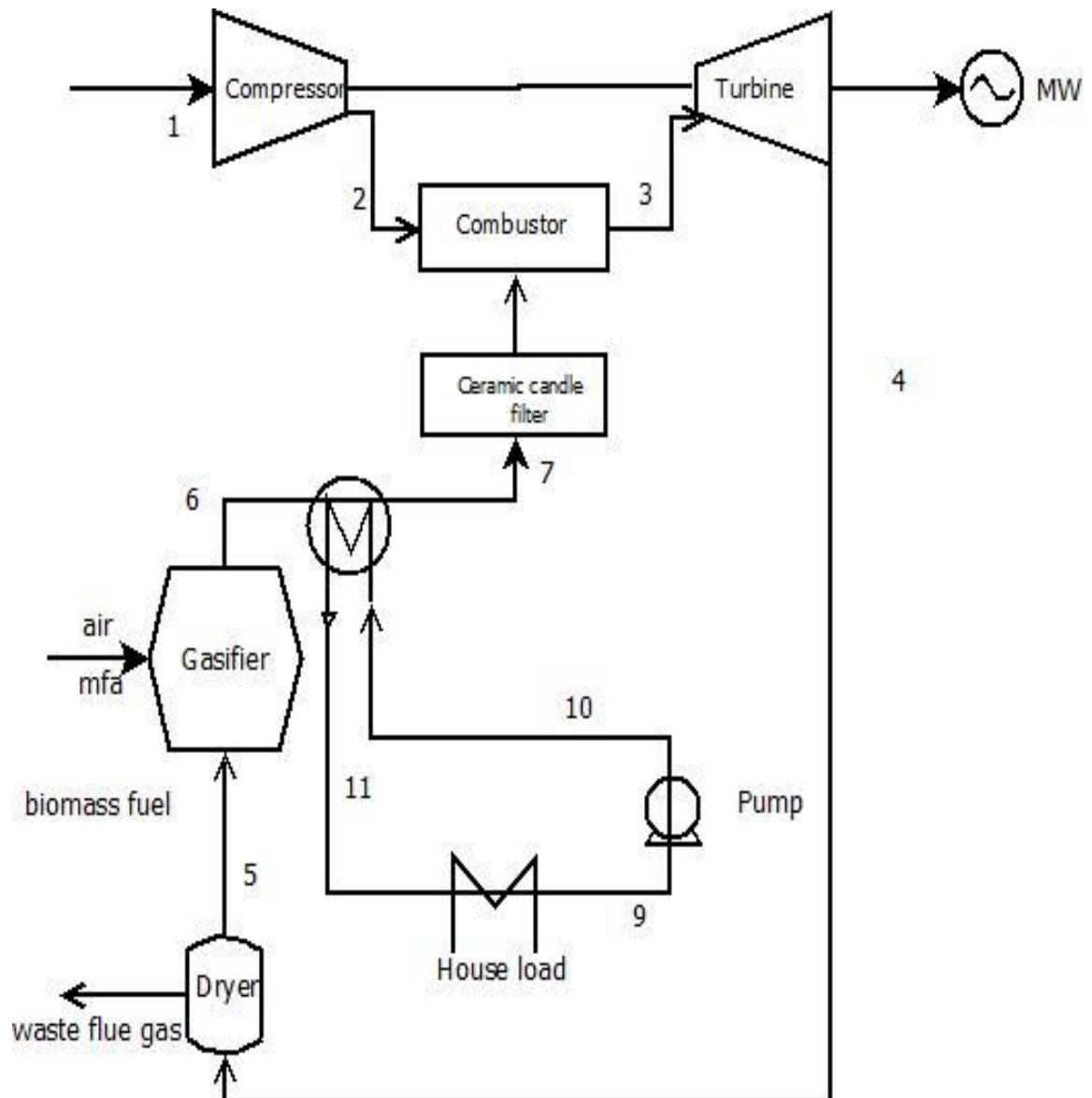
Figure 5.1 Power Plant Layout

5.2.2 Dryer. Every kilogram of moisture in the biomass takes away a minimum of 2260 kJ of extra energy from the gasifier to vaporize water, and that energy is not recoverable (Basu 2010). Although it is hard to remove the inherent cell structure moisture, the surface moisture should be removed to increase efficiency. The flue gas from the turbine is used to dry the biomass fuel using a biomass fuel dryer model no AMS-HG606 (Amisy Group 2012)

5.2.3 Gas Clean Up. Tar is a complex mixture of benzene, toluene, and aromatic hydrocarbon etc. It is produced primarily through de-polymerization during the pyrolysis stage of gasification. Biomass, when fed into a gasifier, first undergoes pyrolysis that can begin at a relatively low temperature of 200C and complete at 500C. In this temperature range the cellulose, hemicellulose, and lignin components of biomass break down into tars. These tars condense at reduced temperature, thereby fouling and disrupting the system (Basu 2010).

To remove these tars from the syngas, a method of gas cleanup must be employed. There are many gas clean-up methods/stages available like cyclones, candle filters, wet electrostatic precipitators, wet scrubber, alkali remover, crackers etc. For this case, gas cleanup was accomplished by cooling the product gas through direct quench to condense alkali species. A hot ceramic candle filter offered by Westinghouse and being demonstrated in the Clean Coal Technology Program is then used for removal of particulate matter including the condensed alkali compounds. Recent tests of tar cracking and this particulate and alkali removal strategy were conducted at the IGT PDU unit in Chicago. Results from these tests indicate that a tar cracker may not be necessary in an eventual commercial system design. Tars are produced in fairly small quantities, and

appear to be substantially cracked prior to reaching the candle filter. The particulate filters tested at IGT also did not experience any plugging problems due to tars, and were successful in reducing the particulate matter and alkali species in the gas stream to very low levels. Therefore, for the purposes of this study quenching followed by the ceramic candle filters was assumed to be sufficient for fuel gas cleaning (Craig and Mann 1996).

5.2.4 Brayton Cycle. The Brayton cycle is one of the popular thermodynamic power cycles used in power industries. It has three major components:

a)   Compressor

b)   Combustion chamber

c)   Turbine

In this study, the syngas from gasifier is combusted in the combustion chamber with the supplied air from the compressor. The combusted gases drive the turbine which is coupled with the generator to produce power.

5.2.5 Heat Exchanger. The purpose of the heat exchanger in between the gasifier and the ceramic candle filter is to reduce the temperature of the syngas to a level that the ceramic candle filter can withstand. For simplicity, a counter flow heat exchanger is used in this study. The syngas is cooled by water circulating in a separate system using a pump. The hot water coming out of heat exchanger can be used for space and water heating (house loads).

	Units	Bean straw (#1223)	Oats straw (#535)	Rapeseed straw(#2817)	Wheat straw (#424)	Rye straw (#547)	Alfalfa (#624)
Ultimate Analysis							
Carbon	Wt. (%)	34.38	37.06	34.21	36.82	37.49	36.07
Hydrogen	Wt. (%)	4.47	3.92	4.25	4.4	4.23	3.93
Nitrogen	Wt. (%)	0.66	0.55	0.45	1.32	0.37	2.64
Oxygen	Wt. (%)	35.94	30.93	37.94	33.15	33.58	28.49
Calorific Values							
Net Calorific Value	MJ/kg	12.50	13.12	12.75	13.28	13.61	13.16
Gross Calorific Value	MJ/kg	13.97	14.47	12.63	14.18	15.03	14.52
Molecular Weight	kg/Kmol	26.34	23.46	26.96	24.67	24.06	23.68

Table 5.2 Fuel properties and composition

5.3 GASIFIER CALCULATIONS

Assuming 100kg of fuel sample and using the properties and composition of the fuel from (ECN 2013), the following composition values were found for the bean straw: 34.38kg of carbon, 4.47kg of hydrogen, 0.66kg of nitrogen and 35.94kg of oxygen.

As 12 kg of carbon makes up 1kmol of carbon, the number of kmol of carbon was determined to be: (34.38kg x1kmol) /12kg =2.86 kmol of carbon. Doing this for the other constituent materials:

- Hydrogen weight of 4.47kg contains 4.47kmol of hydrogen

- Nitrogen weight of 0.66kg contains 0.047kmol of nitrogen

- Oxygen weight of 35.94kg contains 2.25 kmol of oxygen

The assumed empirical formula is normalized for the amount of carbon, so we divide each element by 2.86:

$$x=4.47/2.86=1.56$$

$$y=0.047/2.86=0.017$$

$$z=2.25/2.86=0.784$$

Thus the empirical formula for the bean straw is found to be $CH_{1.56}O_{0.017}N_{0.784}$. The same procedure is repeated for other biomass fuels with the results shown in Table 5.3. It can also be converted to chemical empirical formula by using online tools available (The University of Sydney 2013).

Table 5.3 x, y, and z values in Empirical Formula

Biomass Fuels	x	y	z
Bean Straw	1.56	0.017	0.784
Oats straw	1.269	0.626	0.013
Rapeseed straw	1.491	0.832	0.011
Wheat Straw	1.434	0.675	0.031
Rye Straw	1.336	0.663	0.008
Alfalfa	1.324	0.594	0.063

5.3.1 The Biomass Gasifier Model. The biomass gasifier modeling procedure has already been developed for wood (Jarungthammachote and Dutta 2007) and it has been modified here. The global gasification reaction can be written as equation (1) (Jarungthammachote and Dutta 2007)

$$CH_xO_yN_z + wH_2O + m(O_2 + 3.76N_2) \rightarrow x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + (\frac{z}{2} + 3.76m)N_2$$

(1)
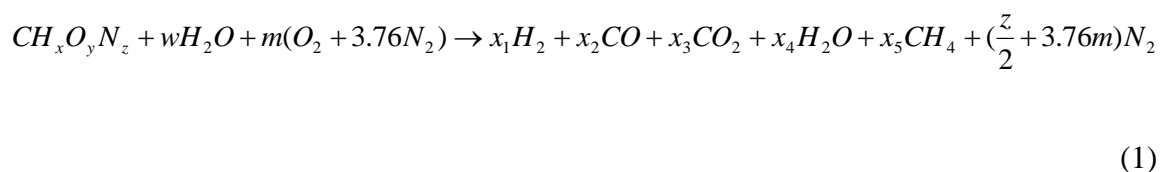
Where:

x=number of atoms of hydrogen per number of atom of carbon in the biomass.

y=number of atoms of oxygen per number of atom of carbon in the biomass.

z=number of atoms of nitrogen per number of atom of carbon in the biomass.

m=kmol of air per kmol of biomass.

w = kmol of moisture per kmol of biomass (found by using equation (2) (Soltani, et al. 2013))

$$\mathbf{w} = \frac{m_{bm}MC}{18(1-MC)} \tag{2}$$

Where:

m_{bm} =mass of biomass in kg/kmol.

MC= percentage of moisture content in biomass.

The calculated w values are given in Table 5.3. All inputs on the left-hand side of eqn (1) are defined at 25°C. On the right-hand side, x_i is the number of moles of species i, and is also unknown.

5.3.2 Mass Balance. To find the five unknown species of the producer gas, five equations were required. Those equations were generated using mass balance and equilibrium constant relationships. Considering the global gasification reaction in Equations (1), the first three equations were formulated by balancing each chemical element as shown in equations (2), (3) and (4) (Jarungthammachote and Dutta 2007)

Carbon balance:

$$f_1 = 0 = x_2 + x_3 + x_5 - 1 \tag{3}$$

Hydrogen balance:

$$f_2 = 0 = 2x_1 + 2x_4 + 4x_5 - x - 2w \tag{4}$$

Oxygen balance:

$$f_3 = 0 = x_2 + 2x_3 + x_4 - w - 2m - y \tag{5}$$

5.3.3 Thermodynamic Equilibrium. Some assumptions need to be made to begin the thermodynamic analysis, which are:

1) The thermodynamic equilibrium was assumed for all chemical reactions in the gasification zone.

2) All gases are assumed to be ideal.

3) All reactions form at pressure 1 atm.

Chemical equilibrium is usually explained either by minimization of Gibbs free energy or by using an equilibrium constant. To minimize the Gibbs free energy, constrained optimization methods are generally used which requires an understanding of complex mathematical theories. For that reason, the present thermodynamic equilibrium model is developed based on the equilibrium constant (Turns 2000) and not on the Gibbs free energy. The gasification process involves the following reactions:

Boudouard reaction (Jarungthammachote and Dutta 2007):

$$C + CO_2 \rightarrow 2CO \tag{6}$$

Water-gas reaction (Jarungthammachote and Dutta 2007):

$$C + H_2O \rightarrow CO + H_2 \tag{7}$$

Methane reaction (Jarungthammachote and Dutta 2007):

$$C + 2H_2 \rightarrow CH_4 \tag{8}$$

By subtracting Equations (6) and (7), we can get the water –gas shift reaction equation (ZA, et al. 2001)

$$CO_2 + H_2O \rightarrow CO_2 + H_2 \tag{9}$$

The remaining two equations are obtained from the equilibrium constant of the reactions occurring in the gasification zone as shown in equations (10 – 12). The equilibrium constant for water-gas shift reaction (Jarungthammachote and Dutta 2007)

$$K_1 = \prod_i (x_i)^{v_i} (\frac{P_g}{P_{atm}})^{\Sigma_i v_i} = \frac{x_3 x_1}{x_2 x_4} \tag{10}$$

The equilibrium constant for methane reaction (Jarungthammachote and Dutta 2007)

$$K_2 = \prod_i (x_i)^{v_i} (\frac{P_g}{P_{atm}})^{\Sigma_i v_i} = \frac{x_5 x_{tot}}{x_1^2} \tag{11}$$

$$x_{tot} = x1 + x2 + x3 + x4 + x5 + ((\tfrac{z}{2}) + 3.76m) \tag{12}$$

Where:

x_i is mole fraction of species i in the ideal gas mixture,

v is stoichiometric number (positive value for products and negative value for reactants),

P_{atm} is standard pressure, 1 atm,

x_{tot} is total mole of producer gas given in equation (12) (Jarungthammachote and Dutta 2007)

Equations (9) and (10) can be modified to (13) and (14) respectively (Jarungthammachote and Dutta 2007)

$$f_4 = 0 = K_1 x_2 x_4 - x_3 x_1 \tag{13}$$

$$f_5 = 0 = K_2 x_1^2 P_g - x_5 x_{tot} P_{atm} \tag{14}$$

Since the reaction is assumed to take place in high pressure, P_g and P_{atm} are introduced in equation (14)

Where:

Pg=pressure of the syngas =32 bar. This is to match up with the high pressure
design so that the syngas cleanup can be done easily. (Craig and Mann 1996)

Patm=atmospheric pressure=1.013 bar

K1 and K2 values are found out by using Equation (13) and (14) (Jarungthammachote and
Dutta 2007)

$$\ln K = -\frac{\Delta G_T^0}{R_u T} \tag{15}$$

Where:

R_u =8.314 kJ/ (kmol .K) (universal gas constant)

T= Temperature at which gasification occurs and it is assumed to be adiabatic

The gasifier is fluidized bed unit similar to that under development by the
Institute of Gas Technology (IGT) (Craig and Mann 1996) which has an operating
temperature of 1103K. Here the operating temperature is assumed to be 1073K. ΔG_T^0 is
the standard Gibbs function and found by using the equation (16) (Jarungthammachote
and Dutta 2007)

$$\Delta G_T^0 = \sum_i v_i \Delta \bar{g}_{f,T,i}^0 \tag{16}$$

$\Delta \bar{g}_{f,T,i}^0$ represents the standard Gibbs function of formation at given temperature T of the
gas species i. The value for $\bar{g}_f^0$ is zero for all chemical elements at reference state

(298K, 1 atm) and for the elements occurring in natural state. $\overline{g}_f^0$ values are found

through interpolation of tabulated data and given in Table 5.4.

Table 5.4 Values of $\overline{h}_f^0$, $\overline{C}_{p,i}$ and coefficients for $\overline{g}_f^0$

	H$_2$	CO	CO$_2$	H$_2$O	N$_2$	CH$_4$
$\overline{C}_{p,i}$	30.5	33.59	55.07	42.28	33.12	4.64
$\overline{h}_f^0$	0	112458	394817	248314	0	-81613
$\overline{g}_f^0$	0	206656	396024	188599	0	-11264

Equation (16) can be rewritten using water – gas shift reaction (9) and methane reaction (10)

$$G_1 = \overline{g}_{f,CO_2}^0 - \overline{g}_{f,CO}^0 - \overline{g}_{f,H_2O}^0 \tag{17}$$

$$G_2 = \overline{g}_{f,CH_4}^0 \tag{18}$$

K$_1$ and K$_2$ can be calculated from the equation (15) as follows

$$K_1 = \exp\left(-\frac{G_1}{R_u T}\right) \tag{19}$$

$$K_2 = \exp\left(-\frac{G_2}{R_u T}\right) \tag{20}$$

5.3.4 Energy Balance. The temperature of the gasification zone needs to be

calculated in order to calculate the equilibrium constants (Equations (13), (14), (15)). For

this reason, either energy or enthalpy balance is performed for the gasification process

which was usually assumed to be an adiabatic process. When the temperature in

gasification zone is T and the temperature at inlet state is assumed to be 298K (25^0C), the

enthalpy balance for this process is written in equation (21) (Jarungthammachote and

Dutta 2007)

$$\sum_{j=react} \bar{h}^0_{f,j} = \sum_{i=prod} x_i(\bar{h}^0_{f,i} + \Delta \bar{h}^0_{T,i}) \tag{21}$$

Where:

$\bar{h}^0_f$ is the enthalpy of formation in kJ/kmol

$\Delta \bar{h}_T$ represents the enthalpy difference between any given state and at reference

state and given by equation (22) (Turns 2000)

$\bar{h}^0_f$ value is zero for all chemical elements at reference state (298K, 1 atm) and for

elements occurring in natural state.

$$\sum_{i=prod} \Delta \bar{h}_T = \sum_{i=prod} \bar{C}_p \Delta T \tag{22}$$

Expanding equation (22), we get equation (23)

$$\Delta \bar{h}^0_{f,fuel} + w \Delta \bar{h}^0_{f,H_2O} = x_1(C_{p,H2}(T_n - T_1) + x_2(h_{f,CO} + C_{p,CO}(T_n - T_1)) +$$
$$x_3(h_{f,CO_2} + C_{p,CO_2}(T_n - T_1)) + x_4(h_{f,H_2O} + C_{p,H_2O}(T_n - T_1)) + x_5(h_{f,CH_4} + C_{p,CH_4}(T_n - T_1))$$
$$+ ((\frac{c}{2}) + 3.76m)C_{p,N_2}(T_n - T_1)$$

$$\tag{23}$$

Where:

$T_n = T =$ Assumed for easy calculation purpose.

$\bar{C}_{p,i}$ values are found by interpolation and given in the Table 5.3 (Turns 2000)

The $\bar{h}_{f,fuel}^0$ can be found from the equation (24) (Jarungthammachote and Dutta 2007)

$$\Delta \bar{h}_{f,fuel}^0 = LHV_{fuel} + \sum_{i=prod} (\tfrac{x_i}{x_{tot}}) \Delta \bar{h}_{f,i}^0 \tag{24}$$

Where:

LHV$_{fuel}$=lower heating value of biomass fuel in kJ/kmol

Equation (24) can be expanded to equation (25)

$$\Delta \bar{h}_{f,fuel}^0 = ((LHV_{fuel} M_{fuel})/1000) + (\tfrac{x_2}{x_{tot}}) \Delta \bar{h}_{f,CO}^0 + (\tfrac{x_3}{x_{tot}}) \Delta \bar{h}_{f,CO_2}^0 + (\tfrac{x_4}{x_{tot}}) \Delta \bar{h}_{f,H_2O}^0 + (\tfrac{x_5}{x_{tot}}) \Delta \bar{h}_{f,CH_4}^0$$

$$\tag{25}$$

Where:

M$_{fuel}$=molecular mass in kg/kmol

5.3.5 Calculation Procedure. The operating temperature T is assumed to be 1073K and substituted into Equations (19) and (20) to calculate K_1 and K_2. Both the equilibrium are substituted into Equations (13) and (14). Then, the five simultaneous equations (6),(7),(8),(13)and (14) are used and solved by using the EES to obtain the values of x_1, x_2, x_3, x_4 and x_5. For calculating the new temperature of T_n, equations (23) to (25) are used. The procedure is repeated by changing the m value by trial and error method until the temperature T value matches with the new temperature T_n value. The flowchart for the calculation is illustrated in Figure 5.2.

The calculations included in Figure 5.2 are done by assuming the 1kmol of biomass reacting with the air. As the amount of biomass straw produced is assumed to be limited to 2000 ha, the biomass feed rate in kg/s is calculated and listed in Table 5.5.

The Syngas composition for the biomass feed rate is calculated and listed in Table 5.6. The values obtained in IGT (Craig and Mann 1996) are H_2-8.91%, CO-6.71%, CO_2-13.45%, H_2O-39.91%, N_2-24.41%, CH_4-6.51%.The values of H_2, CO and N_2 obtained in Table 5.6 are comparable to IGT.The wood is the biomass fuel in IGT The differences in CO_2, CH_4 and H_2O values in Table 5.6 and IGT are due to the high energy content of wood, different composition of the wood. The syngas produced in IGT is 1.073 m^3/kg of biomass which is comparable to the value in the Table 5.6

Table 5.5 Biomass crops yield and feed rate

Crop rotation	Grain Yield (kg ha^{-1} year^{-1})	Straw Yield (kg ha^{-1} year^{-1})	Straw Yield for 2000 ha(kg year^{-1})	Biomass feed (kg/s)
Field beans	2400	2040	4080000	0.1294
Oats	3200	2720	5440000	0.1725
Green manure/alfalfa	6000	6000	12000000	0.3805
Winter rapeseed	2000	1700	3400000	0.1078
Winter wheat	3500	2975	5950000	0.1887
Green manure/alfalfa	6000	5100	12000000	0.3805
Rye	3200	2720	5440000	0.1725

Figure 5.2 The calculation procedure
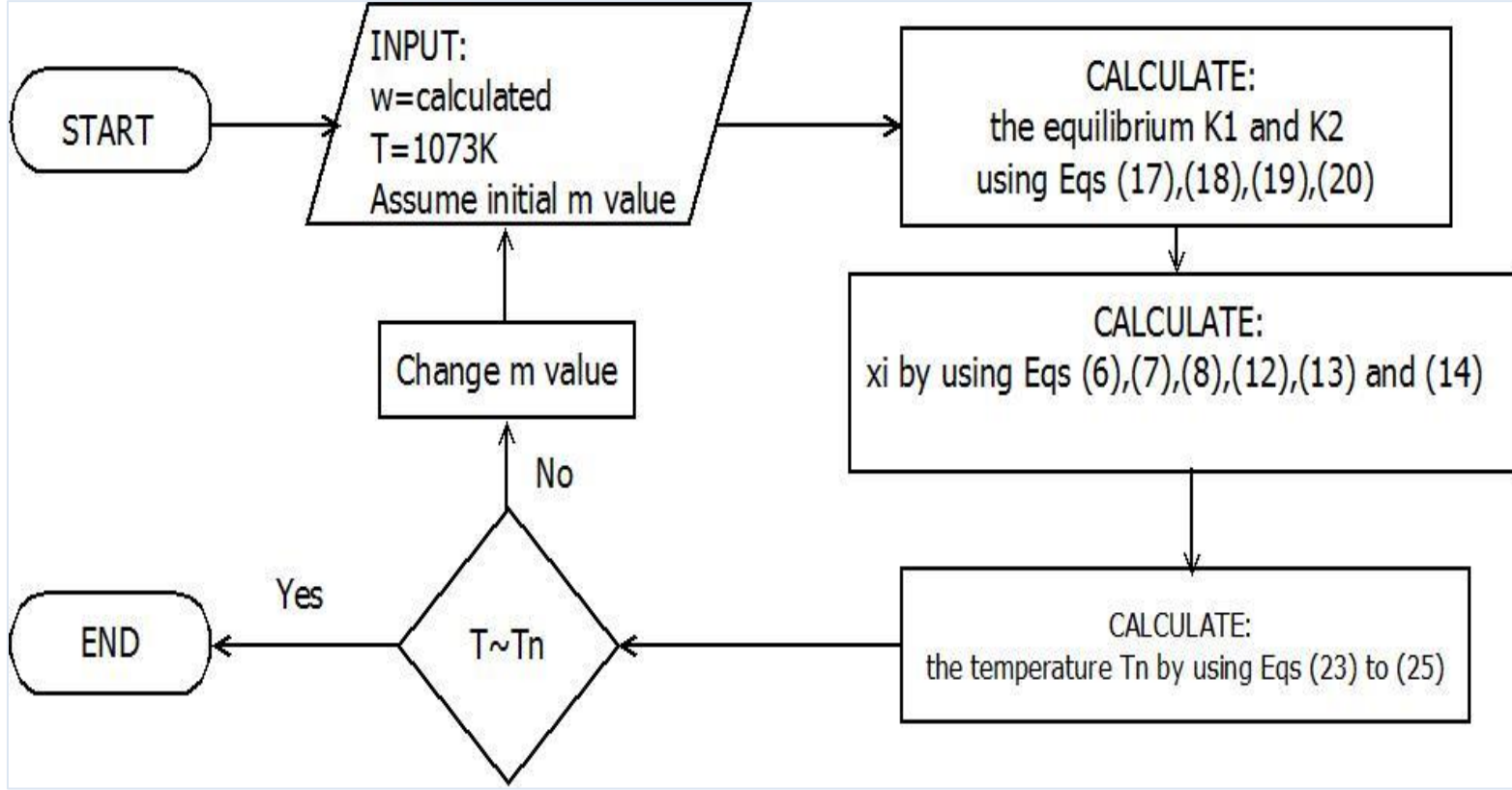
fuel	biomass feed (kg/s)	Syngas m^3/kg of biomass	air for syngas m (kmol)	Syngas output from gasifier (%)					
				x_1 H$_2$	x_2 CO	x_3 CO$_2$	x_4 H$_2$O	x_5 CH4	x_{N2} N$_2$
bean	0.1294	0.79	0.0006	4.25	6.56	26.23	16.06	20.98	25.92
oats	0.1725	0.83	0.0012	4.05	9.54	24.50	9.56	18.58	33.78
alfalfa	0.3805	0.84	0.0018	4.09	9.41	23.33	9.31	18.93	34.93
rapeseed	0.1078	0.81	0.0005	4.28	6.78	28.15	16.29	20.73	23.75
wheat	0.1887	0.85	0.0012	4.24	8.27	25.06	11.79	20.35	30.29
rye	0.3805	0.87	0.0011	4.15	9.09	25.10	10.51	19.45	31.69
alfalfa	0.1725	0.84	0.0028	4.09	9.41	23.33	9.31	18.93	34.93

Table 5.6 Syngas Composition

5.4 COMBUSTION CALCULATION

The combustion reaction in the combustion chamber of the gas cycle is assumed to take place according to Eq (26)

$$x_1 H_2 + x_2 CO + x_3 CO_2 + x_4 H_2O + x_5 CH_4 + (\frac{z}{2} + 3.76m)N_2 + m_1(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + eN_2O + fN_2$$

$$(26)$$
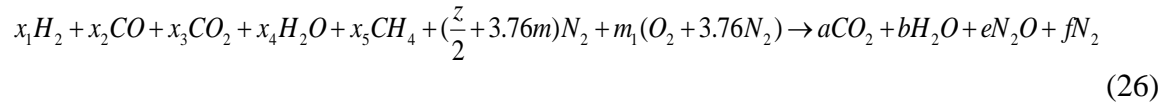
Where:

m₁=kmol of air needed to combust the syngas

The stoichiometric or theoretical combustion equation is obtained by assuming complete combustion using Eq (27)

$$x_1 H_2 + x_2 CO + x_3 CO_2 + x_4 H_2O + x_5 CH_4 + (\frac{z}{2} + 3.76m)N_2 + m_2(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + fN_2$$

$$(27)$$
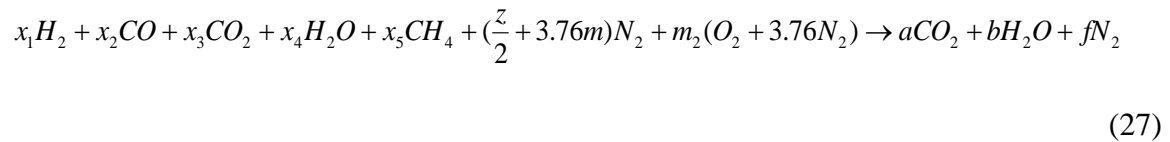
Where:

m₂=kmol of air required for complete combustion.

As an excess amount of air is utilized for the combustion practically, the number of kmol of air m₁ required is calculated by assuming equivalence ratio of ϕ=1.1 and using the equation (28)

$$\phi = \frac{(air / fuel)_{actual}}{(air / fuel)_{stoichiometric}} = \frac{m_1}{m_2} \tag{28}$$

After finding m₁, the values of a, b, e, and f are calculated as follows:

Carbon Balance: a = x₂+x₃+x₅

Hydrogen Balance: b = ({2x₁+2x₄+4x₅})/2

Oxygen Balance: e = {(x$_2$+2x$_3$+x$_4$)+2m$_1$-2a-b}/2

Nitrogen Balance: f = {2[(z/2)+3.76m]+7.52m$_1$-2e}/2

The flue gas composition from the gas turbine is shown in .

5.4.1 Global Warming Potential. Global Warming Potential (GWP) allows scientists and policymakers to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to other gases. GWP of a greenhouse gas is the ratio of radiative forcing (both direct and indirect), from one kilogram of greenhouse gas to one kilogram of CO_2 over a period of time, 100 years in this case as recommended by the Intergovernmental Panel on Climate Change (IPCC) and employed for US policymaking and reporting purposes. CO_2 was chosen as the reference gas to be consistent with the IPCC guidelines.

According to Second Assessment Report (SAR) the GWPs for CO_2 and N_2O are 1 and 310 respectively.

To determine the Carbon Equivalent (CE) of the greenhouse gases (mass):

- Convert Tons of greenhouse gas to kg CO_2 – equivalent =Tons of GHG x GWP

- Convert CO_2-equivalent to carbon Equivalent =Tons CO_2 – equivalent x 0.2727

The calculated values are listed in the Table 5.7.

fuel	biomass feed (kg/s)	air for syngas m (kmol)	Flue Gas from the Gas Turbine (kmol)				CE per year (Ton)		
			a CO_2	b H_2O	e N_2O	f N_2	CO_2	N_2O	Total CE per year
bean	0.1294	0.0006	0.005	0.009	0.002	0.028	1891.97	290346.3	292238.35
oats	0.1725	0.0012	0.0077	0.012	0.002	0.040	2648.76	194103.45	196752.25
alfalfa	0.3805	0.0018	0.016	0.016	0.003	0.070	6054.91	324106.89	330161.80
rapeseed	0.1078	0.0005	0.004	0.004	0.001	0.016	1513.88	79255.46	80769.34
wheat	0.1887	0.0012	0.008	0.008	0.001	0.035	3027.15	164207.11	167234.26
rye	0.3805	0.0011	0.007	0.007	0.001	0.030	2648.76	139359.69	142008.45
alfalfa	0.1725	0.0028	0.016	0.016	0.003	0.070	6054.91	324106.89	330161.80

Table 5.7 Different gas composition in flue gas and the CE per year for CO_2 and N_2O

5.5 ENERGY CALCULATION

For the Brayton cycle analysis, values given by (Craig and Mann 1996) were used as a baseline. This includes the following assumptions:

isentropic state 1-2

P_1= 1 bar

g_c=Specific heat ratio for air=1.4

C_{pa} =Specific heat capacity of air at 300K=1005 J/kg K

Pressure ratio,

$$r_p = \frac{P_2}{P_1} \tag{29}$$

For this analysis, a value of r_p=5 is used (Craig and Mann 1996). This results in a value of 5 bar for P_2.

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(g_c-1)/g_c} \tag{30}$$

Solving for T_2 gives a value of 475.15 K.

Work done by the compressor

$$w_c = \dot{m}_a C_{pa}(T_2 - T_1) \tag{31}$$

Where:

m_a = Mass of the air in the combustor.

As the air required for the combustion varies according to the fuel, the power required will also vary.

State 2-3

Heat input to the chamber

$$\dot{Q}_{in} = \dot{m}_f c_{pa}(T_3 - T_2) \tag{32}$$

Where:

T_3 =1200 K (assumed based on gas turbine operating parameters)

m_f = mass of the syngas fuel in kg

State 3-4

Work done on the turbine,

$$w_t = \dot{m}_f C_{pa}(T_3 - T_4) \tag{33}$$

Where:

T$_4$=Temperature of the flue gas and it is an input to the dryer.

Back-work ratio:

$$r_b = \frac{w_c}{w_t} \tag{34}$$

Thermal efficiency of the cycle:

$$\epsilon_{ther} = \frac{(w_t - w_c)}{\dot{Q}_{in}} \tag{35}$$

Brayton cycle efficiency and turbine efficiency are 30% and 36% respectively (Craig and Mann 1996)

Assuming the Heat exchanger is counter flow and follows equation (36):

$$\dot{Q} = \varepsilon \dot{Q}_{max} = \varepsilon C_{min}(T_{h,in} - T_{c,in}) \tag{36}$$

Where:

C_{min} is the smaller of

$$C_h = \dot{m}_h\, C_{p,h} \tag{37}$$

$$C_c = \dot{m}_c\, C_{p,c} \tag{38}$$

$\dot{m}_h$ =Here it is mass flow of syngas in kg/s

$\dot{m}_c$ = Here it is mass flow of water in kg/s

ε=effectiveness is given by equation (39)

$$\varepsilon = \frac{1-\exp[-NTU(1-c)]}{1-c\exp[-NTU(1-c)]} \tag{39}$$

Where:

$$c = \frac{c_{min}}{c_{max}}$$

NTU= number of transfer units given by equation (40)

$$NTU = \frac{UA_s}{c_{min}} \tag{40}$$

Where:

U=overall heat transfer coefficient= 30 (W/m^2 ^{0}C) (Craig and Mann 1996)

A_s=Heat transfer surface area=40 m^2 (Craig and Mann 1996)

The equation (36) can be written as equation (41)

$$\dot{Q} = \varepsilon \dot{Q}_{max} = \varepsilon C_h (T_6 - T_{10}) \tag{41}$$

In this analysis, C_c is C_{min}

State 10-11

Outlet water temperature of heat exchanger, T_{11} can be found out from the equation (42) as follows

$$\dot{Q} = C_c (T_{11} - T_{10}) = \dot{m}_w c_{pw} (T_{11} - T_{10}) \tag{42}$$

$$T_{11} = T_{10} + (\frac{\dot{Q}}{m_w c_{pw}}) \tag{43}$$

Where:

   m_w=feed water mass flow rate (kg/s)

   C_{pw} =specific heat capacity of feed water (kJ/kg K)

Gas outlet temperature T_7 after cooling from heat exchanger can be found using Eq 44.

$$\dot{Q} = C_h (T_6 - T_7) = \dot{m}_g c_{pg} (T_6 - T_7) \tag{44}$$

$$T_7 = T_6 - (\frac{\dot{Q}}{\dot{m}_g c_{pg}}) \tag{45}$$

State 11-9

House load can be found out from Eq (46)

$$\dot{Q}_{hl} = \dot{m}_w c_{pw} (T_{11} - T_9) \tag{46}$$

State 9-10

Power required to pump the water is calculated as follows

$$\textbf{Power}_{\textbf{pump}} = \dot{\textbf{V}}(\textbf{P}_{\textbf{10}} - \textbf{P}_{\textbf{9}}) \tag{47}$$

Where:

$\dot{V}$=volume flow rate of water (m^3/s)

$\dot{V} = \dot{m}/\rho$

P_{10}=25 bar

P_9=2 bar

It is assumed that the house load consists of two- floors residential building

(7.4kw), the hot water system (1.2 kw) and the workshop (1.7 kw) (Kimming, et al.

2010). So the total house load is assumed to be 10.3kw. The mass flow rate of the water

is varied to achieve this.

fuel	$\dot{m}_g$ (kg/s)	c_g	c_w	c	NTU	ε	T11 (K)	T7 (K)	House Load (kw)	Pump Power (kw)
bean	0.25	254.42	13.95	0.06	4.72	0.98	1064.78	1032.33	10.34	0.08
oats	0.38	379.81	14.23	0.04	3.16	0.95	1038.42	1046.2	10.18	0.08
alfalfa	0.85	854.93	18.14	0.02	1.40	0.74	886.17	1061.05	10.21	0.10
rapeseed	0.20	196.98	13.95	0.07	6.09	0.99	1070.57	1020.05	10.42	0.08
wheat	0.41	408.68	13.95	0.03	2.94	0.94	1030.42	1048.85	9.87	0.08
rye	0.36	361.27	13.95	0.04	3.32	0.95	1043.36	1045.18	10.05	0.08
alfalfa	0.85	854.93	18.14	0.02	1.40	0.74	886.17	1061.05	10.21	0.10

Table 5.8 Temperature, power calculations

State 4-5

The flue gas from the turbine is used to dry the biomass fuel using a biomass fuel dryer model no AMS-HG606 (Amisy Group 2012) and the power consumption is assumed to be 7.5kw regardless of the biomass fuel.

5.5.1 Syngas Air Compressor. Isothermal power is given by

$$Isothermal\ Power = \frac{P_1 Q_f \ln r}{36.7} \tag{48}$$

Where:

$P_1 = 1.04$ kg/cm^2 (Absolute Intake pressure)

Q_f = Free air delivered (m^3/hr) (varies depending on the biomass fuel)

$R = 5$ (compression ratio)

$$Power = \frac{Isothermal\ Power}{\eta} \tag{49}$$

Where:

η=efficiency of the compressor assumed to be 0.8 (Craig and Mann 1996).

The compressor power requirement for the different biomass fuels are shown in Table 5.9.

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Table 5.9 Biomass gasifier compressor power requirement

fuel	Air for syngas (m3/s)	Air for syngas (m3/h)	isothermal power requirement (kw)	compressor input power(KW)
bean	0.069	248.04	11.24	14.05
oats	0.097	347.40	15.75	19.68
alfalfa	0.221	794.16	35.99	44.99
rapeseed	0.055	198.36	8.99	11.24
wheat	0.110	397.08	18.00	22.50
rye	0.097	347.40	15.75	19.68
alfalfa	0.221	794.16	35.99	44.99

5.5.2 Net Power. For the 1000 ha total area the tractor energy consumption is

413,947 MJ for a year (Kimming, et al. 2010). Assuming for 2000 ha land, the tractor

power consumption would be twice (827894 MJ) for a year. Thus the tractor power

consumption is 26.26 kw. As previously mentioned the house load is assumed to be 10.3

kw. The power produced, power consumed for the different operations inside the farm

and the power sent to the grid are listed in Table 5.10.

Fuel	Syngas compressor input power (kw)	Pump power (kw)	Gas cycle compressor (kw)	Power produced (kw)	Power to grid (kw)	Power to grid for year (MW)
bean	14.05	0.08	179.37	562.70	305.29	118.79
oats	19.68	0.08	239.92	758.11	434.51	165.95
alfalfa	44.99	0.10	400.63	1363.00	853.31	318.83
rapeseed	11.24	0.08	97.96	327.98	154.79	63.86
wheat	22.50	0.08	202.96	679.80	390.36	149.84
rye	19.68	0.08	172.33	583.28	327.28	126.81
alfalfa	44.99	0.10	400.63	1363.00	853.31	318.83

Table 5.10 Net power calculation

5.6 REFERENCE STATE

To determine how well the biomass model performs it is compared with the reference case. In the reference case (Figure 5.3), it is assumed that the natural gas is used for the combustion. Methane is the major constituent of the natural gas and so the analysis is performed with this compound. Methane has lower carbon content compared to other hydro-carbons found in natural gas like propane, butane etc. Hence using methane as the fuel will provide a lower limit on the CO_2 emitted from the natural gas fuel. The farm operations are assumed to take place with diesel fuel. The power produced is assumed to be used for operating the pump and the excess power being sent to the grid. The outlet gas from the gas turbine passes through two heat exchangers HEX_1 and HEX_2. The water used for house load passes through HEX_1 and the compressor output air passes through HEX_2. The temperature T_5, T_{10}, T_{11} and T_{out} are calculated for heat exchanger 1 and 2 by following the same procedure as in biomass calculation. The house load is assumed to be 10.3kw like the other biomass fuel. There is no syngas production here and hence the associated equipment like compressor, heat exchanger is not available. As the fuel used in this reference model does not require drying, no dryer is included in the system.

5.6.1 Tractor Emission. The emission (CE) due to the diesel tractor is calculated as follows:

1 kg of diesel =44.8 MJ (The Engineering Tool box 2014)

The energy consumed per year=827894 MJ

The mass of fuel required per year = (1/44.8) x 827894=18479.78 kg

1 kg of diesel in farm operation produces 0.94 kg CE (Lal 2004)

Using these values, the emission due to diesel per year was found to be 18479.78 x 0.94 = 17.37 Ton CE.

5.6.2 Combustion Calculation. The natural gas combustion follows the equation

$$CH_4 + m_1(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + eN_2O + fN_2 \tag{50}$$
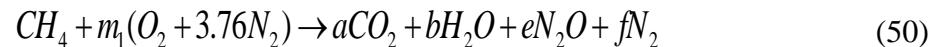
The same procedure is repeated as biomass fuel for calculating emission for CO_2 and N_2O in kg CE. It is found that for CO_2 and N_2O emission are 1891.97 and 586,510.94 Ton CE/year. Thus the total Ton CE per year in the reference state is 588,420.28

5.7 UNCERTAINTY ANALYSIS

To account for variability in the composition of the various biomass fuels, an uncertainty analysis was performed. Biomass composition ranges were obtained by considering different biomass samples from the biomass database (ECN 2013) as shown in Table 5.11. This table gives the lowest and the highest values for the various materials from the database of biomass and waste, which were examined to give a range of possible values that account for the variability in the chemical makeup of the fuels. Uncertainty in CO_2 emission (Ton/year), Total emission (CE/year) and Net power to grid was determined by varying the biomass composition values obtained from different samples and solving for these values.
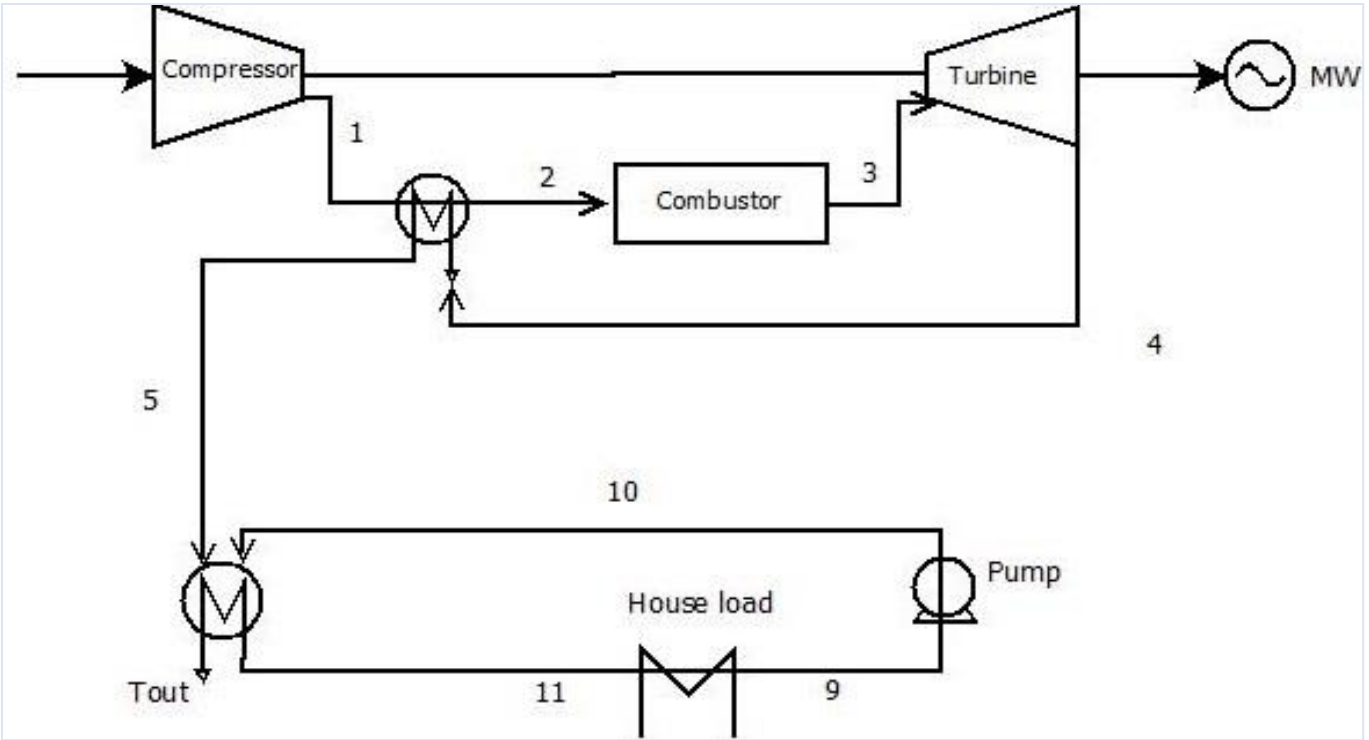
Figure 5.3 Reference state power plant

	Units	Bean straw	Oats straw	Rapeseed Straw	Wheat straw	Rye straw	Green manure / alfalfa
Ultimate Analysis							
Carbon	Wt. (%)	31.04-34.29	36.8-38.08	31.09-33.25	30.8-37.57	37.92-38.08	36.18-36.96
Hydrogen	Wt. (%)	3.85-4.59	4.64-4.73	3.55-4.05	3.9-4.55	4.1-4.9	4.1-4.11
Nitrogen	Wt. (%)	2.9-5.31	0.4-0.9	0.62-0.67	0.3-0.34	0.35-0.45	1.66-2.33
Oxygen	Wt. (%)	26.54-33.49	34.79-34.8	38.91-41.65	23.8-33.82	34.32-34.82	28.22-28.87
Net Calorific Value	MJ/kg	12.20-12.03	13.6-14.47	13.54-13.94	13.16-13.29	11.51-13.13	13.05-14.83

Table 5.11 Biomass composition ranges for uncertainty analysis

6. RESULTS

Figure 6.1 illustrates the CO_2 emissions per year for different biomass fuel. The CO_2 emission for the reference state does not include the diesel emission from the tractor. Figure 6.1 shows that alfalfa has the highest CO_2 emission, followed by wheat, oats, rye and reference. The CO_2 emitted from the biomass combustion is absorbed during the photosynthesis and hence the net CO_2 is zero. CO_2 emitted from the reference state would be higher compared to the biomass fuels.

CO_2 emission uncertainty % is shown in Figure 6.2. Biomass crops like alfalfa, bean, rapeseed and wheat are showing some significant uncertainty percentage.CO_2 emission uncertainty percentage is highest for wheat. But 4% value does not make big difference in the CO_2 emission values.

When the diesel emissions is included in Ton CE for the reference state and add the N_2O emission in the calculation, the total emission in Ton CE is as shown in the Figure 6.3 The reference state shows the highest total emission per year. The second highest would be alfalfa followed by other biomass fuels

Uncertainty percentage for total emission varies up to 10% as shown in Figure 6.4, mainly due to the biomass composition. The syngas and combustion air also contributes to the NOx emissions which in turn increases the uncertainty for the total emissions.

The power sent to the grid in MW /year is given in Figure 6.5. As the turbine inlet and outlet temperatures are constant, the power production follows the total mass flow in the turbine as shown in Figure 6.6.

Net MW/year to grid uncertainty percentage is shown in Figure 6.7. When rye is used as a fuel the uncertainty percentage is the highest (15.53%). The second highest uncertainty percentage was oats followed by alfalfa, beans, rapeseed and wheat. These uncertainties are not only due to the different biomass composition but are also due to changes in air consumption within the gasifier and the combustor. These change in air consumption leads to change in power consumption of the equipment.
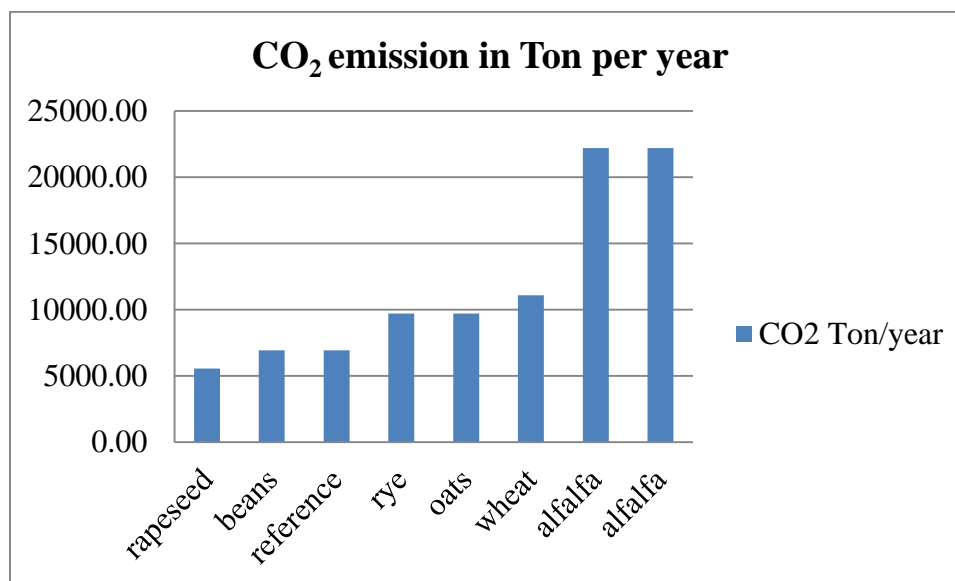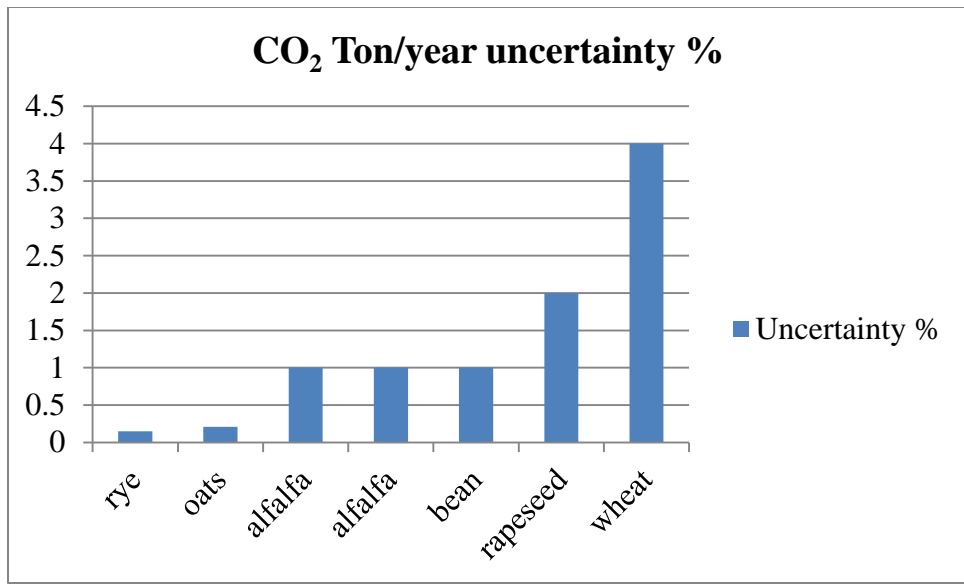

Figure 6.1 CO_2 emission Ton/year
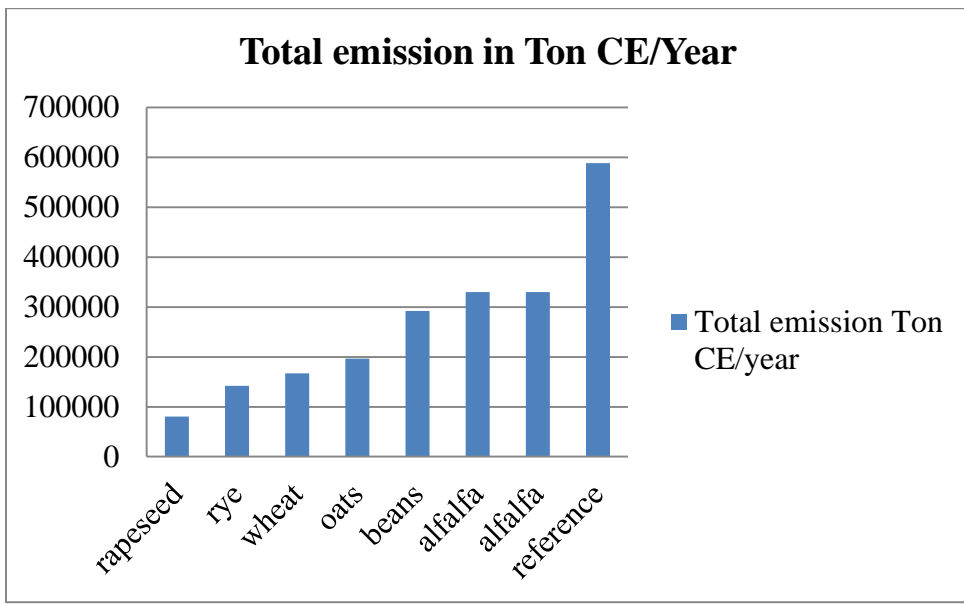
Figure 6.2 CO_2 Ton/year uncertainty %

Figure 6.3Total emissions (Tons/year)
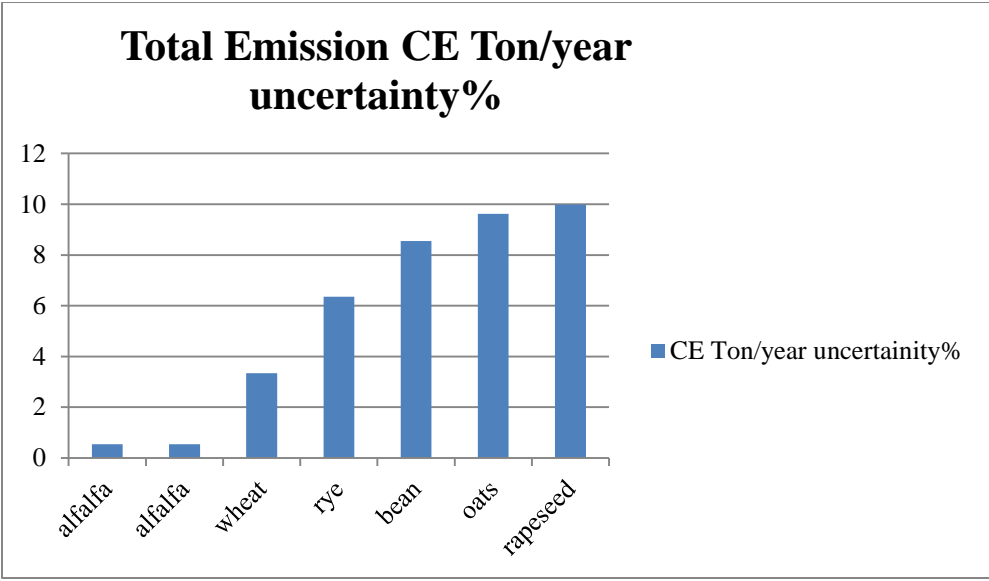
Figure 6.4Total Emission CE (Tons/year uncertainty %)

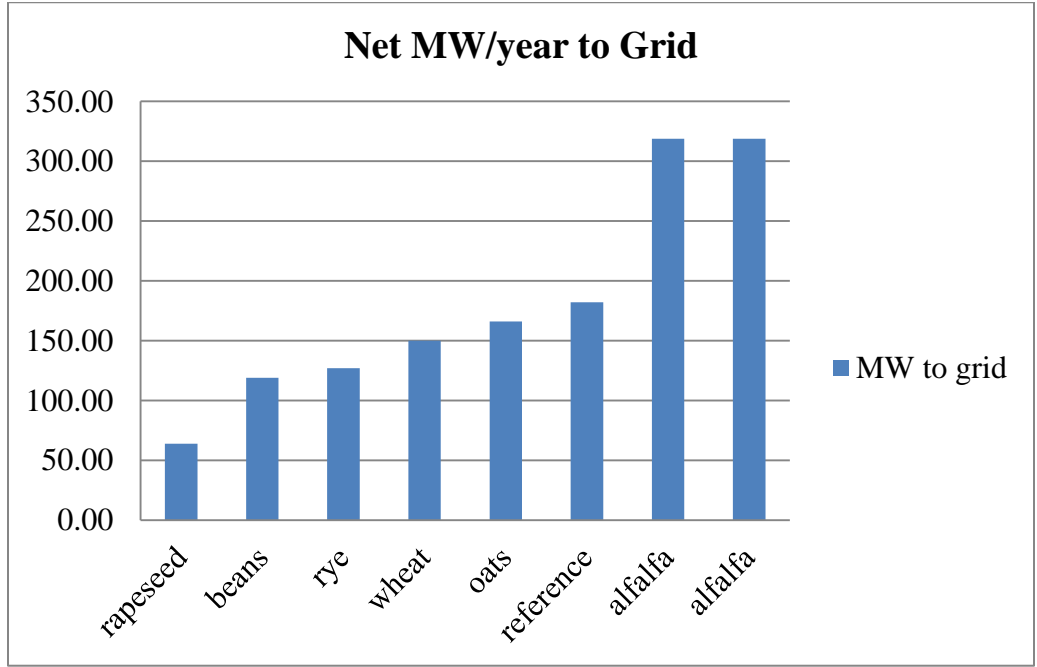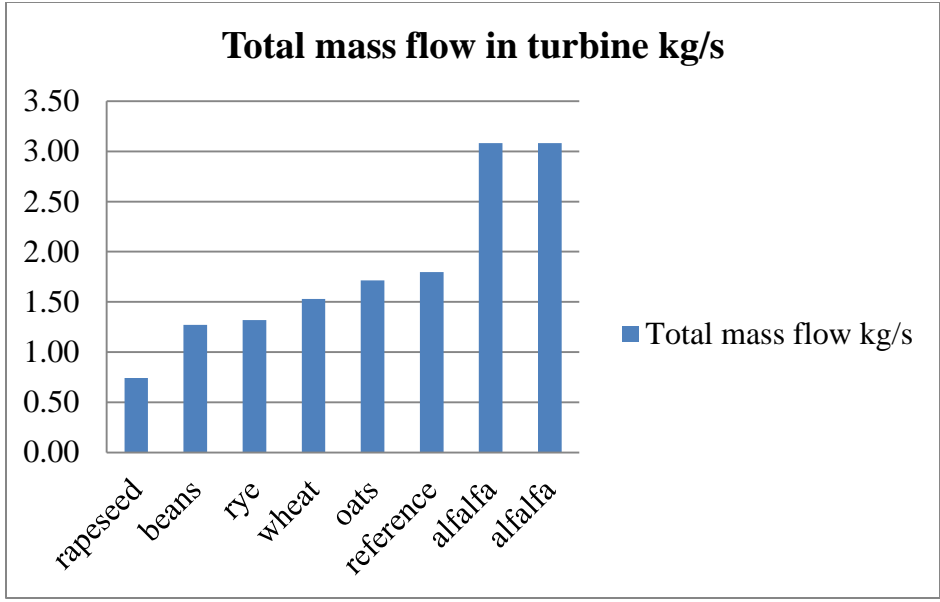Figure 6.5 Net Power produced for different fuels

Total mass flow in turbine kg/s

Figure 6.6 Total mass flow in turbine (kg/s)
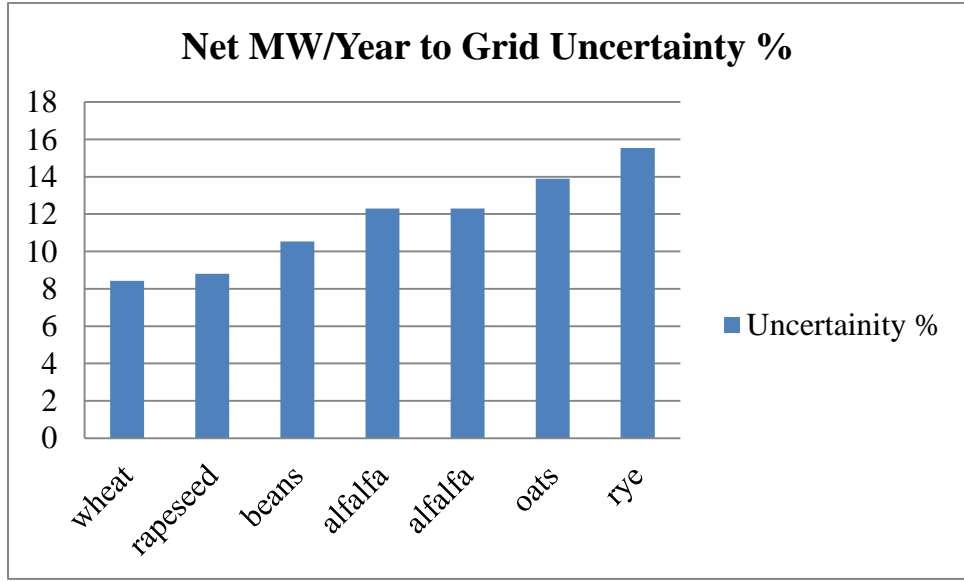
Net MW/Year to Grid Uncertainty %

Figure 6.7 Net MW/year to Grid uncertainty %

7. CONCLUSION

This study demonstrates through energy and emission analysis that it is possible to achieve net CO_2 emission zero in a biomass power plant, although some issues must be considered when using biomass as a standalone fuel. The energy analysis shows that the net power sent to the grid is proportional to the fuel mass flow in the turbine. This indicates that the capacity of the storage space should be the same as the crop which has a higher yield among the rotational crops to maintain a sufficient fuel supply for continued operations. To prevent the use of fertilizers and other products that can contribute to emissions in order to add nutrients, control pests and avoid soil erosion, crop rotation cannot be avoided.

The tractors used for the farm operations and transportation were all electric vehicles powered from the biomass power plant. As a result, the net CO_2 emission is zero. In the reference state, although the CO_2 emission is slightly lower than some of the biomass fuels, the net CO_2 emission will not be zero. Another outcome of this facility configuration would be decreased N_2O emission due to less fertilizer being used. The Environmental Protection Agency (EPA) considers N_2O emission a greenhouse gas and has a method to convert the N_2O in to carbon equivalent. The environmental impact of NO_x emission and its reduction in this type of facility is a topic for future work.

The uncertainty analysis gives values for emissions and electrical generation for a range of biomass compositions. The CO_2 emission, total emission values and energy analysis were found to vary around the values initially obtained using this study, representing natural variation in the fuel composition. While there is variation, it is shown that an excess of electrical energy is produced using only biomass fuels, with

significantly lower emissions that the reference model. Although there is not much variation in the CO_2 emission, there is a possibility of variation in the total emission. This variation is mainly due to the variation in the NOx emission. This variation is not only due to the fuel composition but also due to the amount of air used in syngas and combustion. Uncertainty in energy values are contributed by both the fuel composition and energy consumed by the compressor air syngas and combustion.

The model described in this study is well suited for micro power generation and a micro grid. It works well in the rural area where the land and biomass resources are abundant. The electrification in the rural areas in many parts of the world can be made possible by micro generation and micro grid concept. If the co-operative method of farming is used, the electricity costs can be made cheaper.

Grid overloading is considered to be one of the major impediments for the battery powered vehicles. Micro grids can provide a control capability; hence it can disconnect from the central grid and operate independently. This will allow for the energy generated locally to be used to charge electric vehicles without that energy being transmitted over transmission lines. While this study deals with the farm operations battery powered vehicles, the electricity generated can be used to power other electric vehicles like car, vans, and buses used in the nearby community. As the distance between load and generation is less, the transmission and distribution losses are lower compared to the centralized power generation and grid.

One of the major problems in the biomass power production is that if dedicated energy crops are produced in large scale for the power production, it will eventually replace the food crops making the food price higher. In this study, only the crop residues

are used for the power production and hence food production is not affected. Due to the organic method of farming, the greenhouse gas emitted by fertilizers can be avoided. Also the water contamination by the fertilizer run off is reduced.

The micro generation and grid concept can be extended by adding solar, wind and geothermal with the biomass power according to the availability. If the biomass farming is done in a combination with livestock, there are two benefits available depending on the situation. It can be used as good manure for the agricultural land. If there is a strict odor and water pollution norms, then the livestock waste can be converted to biogas by anaerobic digestion that can be used as a fuel for cooking, space heating and water heating.

The mass per energy is less for the biomass fuels and so it requires more space for the storage compared to fossil fuels. Hence storage of a biomass fuels is a major concern. This study does not deal with the storage. The storage space analysis has to be included in the future study.

The parameters like pressure ratio, efficiencies, heat exchanger size, heat exchanger type used in this study are taken based on the IGT value (Craig and Mann 1996). The variation in these values would definitely impact the output of the process. These parameters can be varied according to the need and the capacity of the power plant. The sensitivity analysis can be included in the future work.

In the agriculture practice some portions of crop residues are left in the field for fixing the nutrients. This study neglected the crop residues left over in the field. It can be included in the future study by combining the food crop rotation with the dedicated energy crops like poplar, wood etc.

This study shows that it is feasible to achieve net zero CO_2 emission in a biomass power plant by using electric vehicles for farm operations and transportation. The rejected heat during power generation is utilized for the domestic space heating, reducing heat loss. In addition, it is possible to produce excess power to be sent to the local community thereby reducing the transmission loss. As the biomass fuel used for power generation is a crop residue, food production is not affected.

APPENDIX

EES code for finding the syngas composition:

```
Patm=1;
Pg=32;
T1=298; "room temperature"
"Input values
change the values for LHV depending upon different fuels"
T=1073; "kept constant"
m=0.146; "This value is adjusted to make Tn constant"
w=0.34; "20% moisture   calculated "

R=8.314; "universal gas constant in kJ/kmol"
"The equation is of the form
C Ha Ob Nc +wH2O+m(O2+3.76N2)----x1H2 +x2CO +x3CO2 +x4H2O +x5CH4+((c/2)+3.76m)N2
"

1=x2+x3+x5;  "carbon balance"

a+2*w=(2*x1)+(2*x4)+(4*x5);"hydrogen balance"

w+(2*m)+b= x2+(2*x3)+x4;   "oxygen balance"

x6=x1+x2+x3+x4+x5+((c/2)+(3.76*m)); "x6 is the total kmoles"

(x2*x4*K1)=(x3*x1);   "water gas shift reaction"

(x5*x6*Patm)=((x1^2)*K2*Pg); "methane reaction"

xN2=((c/2)+(3.76*m));"kmol of nitrogen"

"molar percent"
n1=x1/x6;
n2=x2/x6;
n3=x3/x6;
n4=x4/x6;
n5=x5/x6;
nN2=xN2/x6;




"20% moisture"
"a=1.5611;b=0.7842; c=0.0166;" "bean"
"a=1.2694;b=0.6259;c=0.0128"; "oats"
"a=1.4901;b=0.8317; c=0.0112;" "rapeseed"
a=1.4341;b=0.6753; c=0.0307;  "wheat"
"a=1.3367;b=0.6590;c=0.0083; "  "rye"
"a=1.3241;b=0.5924;c=0.0627;""alfalfa"




"coefficient of hf equation in kJ/kmol taken from turns book"
hfCO=-112457.81;
```

```
hfCO2=-394816.68;
hfH2O=-248314.08;
hfCH4=-81612.5;
```

"gf calculation in kJ/kmol taken from turns book"
```
gfCO=-206656.16;
gfCO2=-396024.41;
gfH2O=-188599.04;
"gfCH4=-50794;"
gfCH4=-11264;
```

"gibbs free enrgy calculation for reaction G calculation--multiplied with 1000 to make it in KJ/Kmol"

```
G1=((gfCO2)-(gfCO)-(gfH2O)); "water-gas shift reaction"
G2=(gfCH4);"methane reaction"
```

"K values calculation"
```
K1=exp(-G1/(R*T));
K2=exp(-G2/(R*T));
```

"LHV of different fuels"
"one of the inputs kj/kg"
 "20% moisture kj/kg"
```
LHVb=12516.4;      "bean straw "
LHVo= 12480.0;    "oat straw"
LHVrs= 13108.4 ;  "rapeseed"
LHVw=13215.2;      "wheat straw"
LHVr= 13645.0;    "rye"
LHVa=12233.8;     "alfalfa "
```

 "molecular weight of biomass fuels in kg/kmol"
```
Mb=26.64;"bean straw "
Mo= 23.46;     "oat straw"
Mrs= 24.95;  "rapeseed"
Mw=24.69;     "wheat straw"
Mr= 24.06;    "rye"
Ma=23.68;     "alfalfa "
```

"hf value for the fuel in kJ/kmol"
```
hffuel=LHVw*Mw*.001+((x2/x6)*hfCO+(x3/x6)*hfCO2+(x4/x6)*hfH2O+(x5/x6)*hfCH4)
"hffuel=LHVo*Mo*.001+((x2)*hfCO+(x3)*hfCO2+(x4)*hfH2O+(x5)*hfCH4)"
```

"Cp values in kJ/kmol"
```
CpH2=30.499;
CpCO=33.59;
CpCO2=55.07;
CpH2O=42.28;
CpCH4=4.64;
```

CpN2=33.12;

"multiply with i=1000 to make it as KJ/Kmol"
hffuel*1+(w*hfH2O)=x1*(CpH2*(Tn-T1))+x2*(hfCO+CpCO*(Tn-T1))+x3*(hfCO2+CpCO2*(Tn-T1))+x4*(hfH2O+CpH2O*(Tn-T1))+x5*(hfCH4+CpCH4*(Tn-T1))+((c/2)+(3.76*m))*CpN2*(Tn-T1);

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VITA

Baburaj Kanagarajan had received his Bachelor's degree in Mechanical Engineering from Coimbatore Institute of Technology affiliated to Anna University, India in May 2009.He had worked as a Mechanical Engineer in a Thermal power plant in India from Aug 2009-Dec 2011.

He had also worked as a Graduate Teaching Assistant in the year 2013 (spring & fall) in Missouri University of Science and Technology for the course-Introduction to design and fabrication. He had been working as a Mechanical Engineering co-op for Monsanto Company in spring and fall 2014. He had obtained his Master's degree in Mechanical Engineering from Missouri University of Science and Technology, Rolla in May 2015.