**Keynote Paper**

**on**

***Economic feasibility and environmental impacts of bioenergy in supporting net-zero energy building (NZEB) in the UK***

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**Background**

Building is one of the major sources of energy consumption and CO2 emission. According to a directive of European parliament (2010/31/EU) building is responsible for the amount of 40% energy consumption and 36% CO2 emission in Europe. Building energy supply is mainly from burning fossil fuel which is the main source of greenhouse gas (GHG) emission. GHG emission in the atmosphere is increasing tremendously due to various human activity including fossil fuel-based energy production. Global warming and climate change are the outcome of this GHG emission which causing detrimental impact on our society, economy and environment. From the very beginning of the industrial revolution GHG emission is causing temperature rise in the atmosphere and consequently numerous harmful effects like sea level rise, extinction of many wildlife species has been occurred.

According to the parish agreement, countries are committed to reduce the emission of GHG for ensuring sustainable development of the world. In the year of 2018 IPCC published a report named ‘Global warming of 1.5oC’ which explains the impacts of the global warming rise by temperature 1.5oC and the path to avoid these impacts by limiting the global temperature rise within 1.5oC. This report outlined that limiting temperature rise within 1.5oC, it is required to reduce the global carbon dioxide (CO2) emission by 45% compared to 2010 level by the year 2030 and ‘net-zero’ emission by the year 2050. To achieve this target, it will require a rapid transition in the sectors of land, energy, transport, buildings and industries (“Sustainable Development Goals,” 2020). The meaning of this transition is to reduce the use of fossil fuels in these sectors for energy supply. Several reports found that this target can be achieved by reducing the demand of energy as well as using renewable and clean source of energy for these sectors. Among the identified energy intensive sectors building is one of the most significant source of energy consumption as building consumes around one third of the world’s total energy (Kaewunruen et al., 2018). Many countries around the world including UK has taken an initiative to implement a concept of Net Zero Energy Building (NZEB) goals into their building code to curb the emission of GHG and reducing the use of fossil fuels by using clean energy in the building generated from the renewable energy sources. NZEB is a modern concept which will ensure the energy efficiency of the building to reduce the overall energy consumption as well as the supply of renewable energy to the building.

In addition to that, NZEB will play a vital role to achieve the UN declared sustainable development goals (SDG). NZEB can actively contribute to achieve several goals of SDG like goal seven of affordable and clean energy by supplying renewable and clean energy to the building, goal nine of industry, innovation and infrastructure as the NZEB is a smart building infrastructure, goal eleven of sustainable cities and communities as the NZEB will ensure the sustainable building in the urban and rural areas and finally goal thirteen of climate action as the NZEB will use the energy from the renewable sources which will reduce fossil fuel consumption and significantly contribute to curb the CO2 emissions and consequently will save the planet from the adverse effects of climate change.

**Net Zero Energy Building (NZEB)**

In the recent years NZEB has gained increased attention in many countries energy policy as this is considered as the potential solution to the energy saving, environmental problem and CO2 emission reduction in the construction and operation of building. The NZEB is a conceptual understanding of a kind of energy efficient building which can generate electricity from renewable sources under on-site or off-site generation to meet its energy demand. The term net indicates that there is a balance between energy taken and supplied back to an energy grid over a period. NZEB is connected with a carbon neutral grid to take energy for its operation when its demand is higher than its generation as well as supply back to the same grid when it generates more than its demand. Thus, contributing to supply renewable energy to the national grid. At the same time this green energy supply could be a source of financial benefit for the building owner. Conventional definition of the NZEB describes that the annual operational energy of the building is greater or equal to the on-site renewable energy generation of the building. The concept of the NZEB can be described by the following illustration:



Figure 01: Conceptual illustration of NZEB (Sartori et al., 2012)

**NZEB Supported by Bioenergy**

Energy supply to the NZEB could be achieved by using various renewable energy technologies like solar, wind or bioenergy. Among these technologies’ bioenergy is one of the most promising technologies to achieve NZEB as bio-energy accounts for world’s 12% renewable energy. Bioenergy is defined as the kind of renewable energy which is derived from biomass like plant or plant derived materials like wood. Other kind of biomass is agricultural waste, municipal solid waste, industrial waste or food waste etc. Depending on the kind of biomass, various technologies like pyrolysis, gasification, incineration, anaerobic digestion or land filling can be used to convert energy from biomass. Among the various kinds of biomass food waste is one of the promising sources of renewable energy as UK produces 4.9 Mt of food waste annually which is equal to 73kg per person per year (Quested and Parry, 2015). Anaerobic digestion (AD) of food waste is the most common treatment method of food waste in UK. AD has several advantages to use as food waste treatment method like it works as a sustainable way of food waste management, it generates biogas which could be used later to produce renewable electricity and heat. In addition to that, digestate produced as biproduct from AD can be utilised as organic fertilizer to replace mineral fertilizer. Biogas produced from AD can be easily utilized in CHP plant to produce heat and electricity which could be later used in a building to achieve the goal of NZEB. According to a report of UK parliament in the year 2017, 44% of UK household are practising separate food waste collection and Government supported waste and resource action plan (WRAP) has recommended to increase this practice. AD of food waste in UK could be a potential option to design NZEB coupled with CHP plant which will significantly contribute to provide clean energy in the building operation as well as to the national grid in case of excess generation.

1. **Methodology**
	1. **System Description**

In this study a local community in UK is assumed where 25000 ton of food waste per year is collected in an AD plant with a lifetime of 20 years located in this community. Food waste from every household of this community is transported to the AD facility with waste collection truck. These food wastes are then treated in the AD facility in a mesophilic condition as most of the AD facilities (86%) in UK operate under this condition (Slorach et al., 2019b). Biogas is produced from this AD facility which is utilized in a CHP plant to generate heat and electricity. As this heat and electricity is generated from a renewable source, it will be used to meet the operational energy demand of a building to achieve the goal of NZEB. After meeting the energy demand of that building, excess heat and electricity which is clean energy could be sold to other houses or national grid to earn revenue. Digestate produced as biproduct of the AD process will be transported to the agricultural land to use as replacement of mineral fertilizer. Summary of process and operating parameter of the proposed AD is given in the following table and the concept are sourced from (Ascher et al., 2020):

|  |  |  |
| --- | --- | --- |
| Parameter | Value | Source |
| Feedstock input (ton/year) | 25000 | Calculated |
| Biogas yield (Nm3 /t ww) | 190 | (Ascher et al., 2020) |
| CH4 content (%) | 65 | (Ascher et al., 2020) |
| CO2 content (%) | 35 | (Ascher et al., 2020) |
| Energy density (KWh/m3) | 6.25 | (Ascher et al., 2020) |
| Digestate production (t/t ww) | 0.5 | (Ascher et al., 2020) |
| Efficiency (Electrical, %) | 33 | (Pöschl et al., 2010) |
| Efficiency (Thermal, %) | 50 | (Pöschl et al., 2010) |
| Parasitic load (Electrical, %) | 7 | (Pöschl et al., 2010) |
| Parasitic load (Thermal, %) | 25 | (Pöschl et al., 2010) |

Table 01: Process and operating parameter of the proposed AD and CHP facility

The plant is assumed in a community where around 350000 people live. Taking yearly food waste production per person as 73 kg (Quested and Parry, 2015) total feedstock input is calculated. AD decomposes the food waste (FW) in an oxygen free environment and produces biogas (methane + CO2) and digestate. It is assumed here that the auxiliary heat and electricity demand for running AD and CHP facility is taken from the produced energy of this plant.

* 1. **Waste Collection and Transport System**

Waste is collected from the community using diesel trucks. Environmental impacts from using these trucks is not significant but the cost associated with the waste collection has significant impact on economic feasibility. For calculation of emissions from using diesel in collection it is required to estimate the diesel requirement per functional unit. Environmental impacts from wear of tyres, leakage of diesel oil and braking are not considered in this study. Diesel consumption for waste collection depends on several factors like distance of AD plant from collection point, speed of truck, acceleration/ deceleration, number of stops/go and the driver’s efficiency. The model of waste collection and transport for this study is used from (Larsen et al., 2009) where diesel consumption for 1 ton of waste and emissions from diesel consumptions are studied in Denmark for 14 different schemes and 254 measurements. A conceptual model of this study is as like as:



Figure 02 : Waste collection model (Larsen et al., 2009)

(Larsen et al., 2009) studied diesel consumption for waste collection and observed for different locations like from city area, rural areas and small towns. It is estimated from this study that the average diesel consumptions for 1 ton of waste varies from 1.6 litres for apartment buildings to 10.1 litres for rural areas. For this study it is assumed that the diesel requirement per functional unit is 10.1 litre.

**1.3 Life Cycle Assessment (LCA)**

LCA is the most developed and widely used environmental impact assessment tool for a system or process throughout its whole life cycle. LCA estimates the total amount of energy, wastes, emission associated with the complete life cycle of a product or process. Guidelines according to ISO 14040/14044 is applied in this study to carry out LCA. The goal and scope, inventory data, various sub-processes and necessary assumptions associated with this LCA study is explained in the following sections.

**1.3.1 Goal and Scope definition**

The goal of this LCA study is to identify the environmental impacts of community based distributed food waste treatment system using AD in UK for different impact categories like global warming potential (GWP), acidification potential (AP) and particulate matter formation (PMF). These impacts associated with other processes like utilizing biogas in CHP unit to produce electricity and heat, using digestate produced from AD in the agricultural farmland will also be considered in this study. Finally, the impact associated with the generation of same amount of heat, electricity and mineral fertilizers in the conventional way using fossil fuel will be compared as avoided emissions. This comparison will inform us the overall environmental feasibility of displacing the heat and electricity using this process of AD and CHP for achieving NZEB in the UK.

The scope of this study consists of the following processes:

* food waste collection and transportation to AD plant;
* food waste treatment process in AD plant;
* generation of heat and electricity by combusting biogas in CHP plant;
* digestate transport and use as alternative to mineral fertilizer in farmland.

The environmental impacts for the construction of AD and CHP plant is not considered in this study.

**1.3.2 Functional unit and System boundary**

In case of multifunctional process in LCA study different functional units can be considered depending on the scope of the study. For this study 1 tonne food waste treatment is considered as functional unit. That means, all the environmental impacts, heat, electricity, digestate production will be analysed for one tonne of food waste treated in the AD facility. For the purpose of analysis, the amount of heat, electricity and mineral fertilizer displaced by treating 1 tonne of food waste as well as the avoided environmental burdens by replacing these energies and processes will be considered in this study. System boundary consists of household food waste collection and bringing these to AD facility. The impact of food waste generation process is excluded from the system boundary. In the AD facility biogas and digestate are produced. Biogas is transferred to the CHP unit to generate heat and electricity. Heat and electricity are used to displace the heat and electricity produced from conventional sources (natural gas). All the environmental burdens avoided by using the biogas will be included in the system boundary to calculate the net environmental impacts. On the other hand, digestate production from AD is also included in the system boundary. Digestate will be used in the farmland to replace mineral fertilizer. Avoided environmental impact will be considered here for replacing mineral fertilizer. The flow chart of this system boundary is given in the following diagram:

Replacement

of

Food waste hauling to AD facility

Food Waste

(1000 kg)

Biogas

Mineral Fertilizer

Digestate

Heat and Electricity from Natural Gas

Heat and Electricity

Figure 03: System boundary with process flow chart

**1.3.3 Life Cycle Inventory Data Assumptions**

Key life cycle inventory data like waste haulage distance, emissions from transporting waste, emissions from AD and CHP facility are sourced from existing literature and other reliable sources like government website or international organisation website. Relevant data for different subprocesses shown in the system boundary will be collected and environmental burden of these processes and associated avoided burden will be calculated to carry out LCA. In this study GHG namely CO2, CH4, N2O are considered for calculating net GWP. Net GWP calculation is done based on the GWP of different emissions by converting their global warming potential equivalent to CO2 with characterisation factors. Air pollutants namely RSP (respirable suspended particulate) are calculated in terms of PM10 and NOx. Same conversion procedure is considered for calculating AP equivalent to SO2. CO2 emissions from a source of biologically based material by combustion or decomposition other than combusting fossil fuels are known as biogenic CO2 emissions (US, EPA, 2011). In respect of global warming potential biogenic CO2 is considered neutral as this CO2 is the part of renewable carbon cycle. Throughout this study, the GWP of biogenic CO2 is taken as 0 and GWP of CO2 from burning fossil fuel is taken as 1 (Ascher et al., 2020). For the illustration of GWP of the whole process GWP with and without biogenic CO2 will be depicted for comparison which will show the avoided environmental burden for using biogas to generate heat and electricity other than natural gas. The impacts of GWP, AP and RSP are studied as these are the most significant emissions from waste treatment sector.

All these conversion factors used for the calculation of environmental impacts (GWP, AP, PMF) are listed in the following table:

|  |  |  |  |
| --- | --- | --- | --- |
| Impact | Emission | Characterisation factor | Reference |
| GWP (CO2 eq) | CO2, CH4, N2O | CO2=1, CH4= 28, N2O= 265 | (Ascher et al., 2020) |
| AP (SO2 eq) | SO2, NO2 | SO2 = 1, NO2 = 0.7 | (Ascher et al., 2020) |
| PMF (PM10 eq) | PM10, NOx | PM10=1, NOx = 0.88 | (Ascher et al., 2020) |

Table 02: Conversion factors for different environmental impacts

**1.3.3.1 Anaerobic Digestion Facility**

AD system consists of the unit like AD unit, biogas utilization unit with biogas engine and digestate collection tank. For this study an AD unit of single stage mesophilic reactor with a capacity of 25000 ton per year is considered. The system requires to maintain in a temperature around 35oC to achieve mesophilic environment. The amount of biogas produced in AD facility depends on the composition of feedstock and treatment environment. In this study, biogas composition is taken as 65% methane and 35% CO2. Trace amount of methane losses from the digestion process which is known as the fugitive emission of methane. The amount of methane leakage from the process vary from one plant to another and it can be as high as up to 7% (Patterson et al., 2011). Some studies found that this amount of leakage could be 0%. Based on the reviewing of different existing literature the fugitive emission of methane is taken as 3% in this study.

**1.3.3.2 Waste Collection**

Diesel requirement per functional unit is calculated according to the model described in section 3.2. Emissions from collection truck of Euro iv model for each litre diesel consumptions are listed here:

|  |  |  |
| --- | --- | --- |
| Emission | Unit | Amount |
| CO2 | g/L | 2629 |
| SO2 | g/L | 0.08 |
| NOx | g/L | 17 |
| CO | g/L | 2.2 |
| PM | g/L | 0.1 |

Table 03 : Emissions from collection truck (Larsen et al., 2009)

Environmental impacts from these emissions are calculated using characterization factors. Impacts associated with these emissions will be discussed in the result section.

**1.3.3.3 Combustion of Biogas in CHP unit**

Biogas produced from AD facility can be utilized by using different conversion processes. In this study it is assumed that the biogas is used in CHP unit to produce electricity and heat. The conversion efficiency used here is 33% for electricity and 50% for heat. The combustion reaction in the CHP unit is as like as (Ascher et al., 2020):

CH4 + 2O2 = CO2 + 2H2O

CO2 emission in this reaction is known as biogenic CO2. Small fraction of CH4 emits from the system as unburnt. Other emissions like carbon monoxide, nitrous oxide and particulate matter also emits from the combustion. All the amounts of emissions are taken from the existing literature and listed in the table 03.

|  |  |  |
| --- | --- | --- |
| Emission(g/m3) | Process | Source |
| CHP (direct emission) | AD (fugitive emission) |
| CO2 (biogenic) | 1838.750 | 19.341 | (Ascher et al., 2020) |
| CH4 | 10.463 | 13.026 | (Ascher et al., 2020) |
| CO | 2.588 | - | (Evangelisti et al., 2014) |
| NOx | 3.330 | - | (Evangelisti et al., 2014) |
| NMVOC | 2.363 | - | (Evangelisti et al., 2014) |
| PM10 | 0.860 | - | (Evangelisti et al., 2014) |

Table 04: Emissions from burning biogas in CHP unit (Ascher et al., 2020)

**1.3.3.4 Displacement of Electricity and Heat**

Biogas produced in the AD facility is used to generate heat and electricity which will displace the heat and electricity produced by using natural gas. Natural gas is one of the main contributors in the UK energy grid. The amount of electricity and heat generated from the biogas can be calculated from the data listed in table 01. For the purpose of heat and electricity calculation conversion efficiencies and auxiliary demand of the plant are considered. By considering biogas yield and energy per m3 of biogas it is found that the amount of electricity displacement is 364.45 KWh and heat displacement is 445.32 KWh. The environmental impact (GWP, AP, PMF) for every KWh of energy generated in UK is collected from different literature and listed in the following table:

|  |  |  |  |
| --- | --- | --- | --- |
| Impact | Unit | Amount (CCGT) | Source |
| GWP | Kg CO2/KWh (Electricity)Kg CO2/KWh (Heat) | 0.490.26 | (Fruergaard et al., 2009) |
| AP | Kg SO2/ KWh | 0.00058 | (Evangelisti et al., 2014) |
| PMF | Kg PM10 /KWh | 0.00033 | (Slorach et al., 2019b) |

Table 05: Environmental impact of energy production in UK

For calculation of net environmental impact from heat and electricity displaced by biogas generated heat and electricity can be calculated using data in table 02 and 04.

**1.3.3.5 Utilization of Digestate as Fertilizer**

Digestate is produced in the AD facility as biproduct. Digestate is then transported to the farmland. Emissions associated with environmental impacts are estimated from the amount of diesel use to transport from AD facility to farmland and distribute digestate to the farmland. For the calculation of diesel consumption and GWP regarding digestate application, procedure used in (Møller et al., 2009) is sourced for this study. It is assumed that the digestate need to transfer 25 Km from AD facility. Taking typical diesel consumption for every tonne of digestate per km as 0.3 L, diesel requirement for every ton of digestate is 7.5 L. Considering GWP for 1 L of diesel combustion as 2 kg CO2 eq (Møller et al., 2009), GWP for every ton of digestate application is 15 kg CO2. Other environmental impacts are calculated using emission per litre of diesel fuel mentioned in table 03. All these impacts and resultant impacts will be discussed in the result section.

In addition to that, there are emissions and avoided emissions for using digestate as fertilizer in the farmland. The environmental impacts are calculated according to the steps explained in reference (Møller et al., 2009). Total amount of C, N, P and K per tonne of FW is calculated according to the data listed in the following table:

|  |  |  |
| --- | --- | --- |
| Parameter | Unit | Amount |
| TS | g/kgFW | 248.6 |
| C | g/kgTS | 469.1 |
| N | g/kgTS | 30.7 |
| P | g/kgTS | 3.8 |
| K | g/kgTS | 11.4 |

Table 06: Characteristics of food waste (amount of TS, C, N, P, K) (Tampio et al., 2015)

It is assumed that the nutrients content in the feedstock remain unchanged in the digestate. The amount of C is reduced due to the loss of C in the form of biogenic CO2 in CHP facility. According to the value of the parameter given in the above-mentioned table C content in the 1ton feedstock is 116.62 kg. C loss as biogenic CO2 as value mentioned in table 03 is 96.2 kg. That means C content in the digestate is 20.42 kg which is equivalent to 75 kg biogenic CO2. Avoided emission for the storage of carbon is -10.5 kgCO2 eq tonne ww-1 (coefficient of C storage is taken here as 0.14) which is also known as avoided GWP. N content in the digestate is 7.63 kg. Taking emission factor of N2O – N as 0.017, N2O emission from digestate is 130 g. That corresponds to a GWP of 34.45 kgCO2 eq.

In addition to that, there are avoided emissions for replacing N, P and K fertilizer with digestate in the farmland. The emission factor for the production N, P and K fertilizer are 8.9 kgCO2 kg-1 N, 1.8 kgCO2 kg-1 P and 0.96 kgCO2 kg-1 K respectively (Møller et al., 2009). Taking the amount of substituted fertilizer by digestate as 7.63 kg N, 0.95 kg P and 2.84 kg K respectively for every tonne of FW from the above table 06 the avoided emission for each kind of fertilizers are 67.9 kg CO2 eq tonne FW-1 for N fertilizer, 1.7 kg CO2 tonne FW-1 for P fertilizer and 2.72 kg CO2 tonne FW-1 for K fertilizer. The resultant GWP for replacing these kinds of fertilizer is -72.32 kg CO2 eq tonneFW-1. Consider all the impacts of digestate application net GWP is calculated and it is found as -33.37 kgCO2eq/tonne of food waste. Negative sign indicates avoided emission by using digestate as fertilizer.

**1.4 Economic Analysis**

AD facility considered in this study can treat 25000 t of food waste per year in a community of UK. Biogas produced from AD will be used to produce heat and electricity in a CHP facility. The project timeline of operation is considered as 20 years. Besides biogas AD produces digestate which can be used as organic fertilizer to replace mineral fertilizer. The purpose of this analysis is to measure the economic feasibility of AD system which will give a clear idea of economic feasibility about making decisions to achieve NZEB using AD of food waste. The economic benefit from AD system is reducing the cost of using fossil fuel for generation of heat, electricity and fertilizer. Besides these incomes, AD facility could be benefited by charging tipping fees (gate fees) for the disposal of waste. Income from AD facility varies according to the biogas yield and energy output of the system as well as rate of sale of heat, electricity, digestate and tipping fees. Cost associated with the AD plant are capital cost and operation cost. These costs and revenues can be divided as like as following table:

|  |  |
| --- | --- |
| Cost | Revenue |
| Capital cost* Plant installation
* Interest rate
 | * Income from heat sale
* Income from electricity sale
* Income from digestate sale
* Income from tipping fee
 |
| Operation cost* Feed stock
* Plant maintenance
 |

Calculation of net revenue is done using all these costs and revenues. All cost and income over the lifetime of 20 years is converted to present value with a discount rate 6% (Ascher et al., 2020). Adding all these present values will give the NPV value of the project. NPV will indicate the economic desirability of the project. NPV is the sum of expected cash flows over the whole lifetime of the project. NPV is calculated using the following classic equation (Gebrezgabher et al., 2010):

 NPV= $\sum\_{t=0}^{N}\frac{NCF}{\left(1+r\right)^{N}}$ or -I + $\frac{A}{r}\{1- \frac{1}{\left(1+r\right)^{N}}\}$………………………………………………... (i)

Here, NCF is the net cash flow, r is the discount rate and N is the lifetime period, A is annual cash flow and I is the initial investment of the project. If the value of the NPV becomes positive, project will be economically viable. In case of negative value of NPV, project will not be economically feasible.

**1.4.1 Capital cost (Capex)**

According to the study carried out by (Vasco-Correa et al., 2018) capital cost for AD installation in UK region is mentioned as $ 222 – 571 /ton feed stock for annual plant capacity of 5500 – 110000 ton per year, converting it for pound sterling (£) capital cost for this study is assumed as £ 180 / ton food waste. Total capital cost for 25000 tonnes of food waste is estimated according to this assumption.

**1.4.2 Operation and maintenance cost (Opex)**

Opex includes the feed stock cost and plant maintenance cost. Feedstock cost includes waste collection cost which consists truck purchase and fuel requirement for truck maintenance as well as labour cost. According to (Vasco-Correa et al., 2018) plant operation cost is $ 18 -101 / ton food waste and feedstock cost is USD 44-53 /ton feedstock. Converting these values to pound it is assumed that the plant operation cost as £ 13 /ton waste and feedstock cost as £35 /ton waste for this study.

**1.4.3 Revenues from heat and electricity**

Electricity and heat generated from CHP facility will be used to supply heat and electricity to the nearby building for achieving NZEB. The cost related to heat and electricity supplied from national grid is considered as revenues as the costs are saved for NZEB. Average rate of electricity and heat is taken as 14.37 p and 3.80 p per KWh respectively for this study (“Compare Gas and Electricity Prices per kWh | UKPower,” n.d.). Revenues from supplying at NZEB is estimated using these rates and the excess heat and electricity could be sold as per FiT scheme. The rate of FiT is 4.5p/KWh electricity and 1.4p / KWh heat (ofgem, 2019).

**1.4.4 Revenues from selling digestate**

Digestate can be used as replacement of mineral fertilizer. Digestate production is taken as half of the feedstock and annual digestate productions is 12500 tonnes. Assuming rate of digestate as £13/ ton (Ascher et al., 2020) total revenues from digestate is estimated.

**1.4.5 Revenues from tipping fees**

Tipping fees or gate fees is defined as a levy imposed upon waste to take it into the waste treatment facility. Tipping fees varies according to the nature of waste treatment method. For AD it is assumed that the tipping fee is £ 29 / ton waste (Slorach et al., 2019b). Annual tipping fees is calculated for 25000 tonnes of waste received per year.

**1.4.6 Probable revenues from carbon trading**

AD system is eligible for earning credits by carbon trading as this technology reduces the GHG emissions and fossils fuel use. According to carbon trading mechanism it is possible to earn revenues for every ton CO2eq emission reduction. Assuming £ 50 for every tonne of CO2eq saving as carbon credit for this study (Ascher et al., 2020) total probable carbon credits could be found.

1. **Result and Discussion**

**2.1 Achieving goal of NZEB**

The estimation of energy generation by treating 25000 tons of food per year gives annual electricity generation 9.12x106 KWh and annual heat energy generation 11.12x106 KWh. These amount of heat and electricity can be used to supply heat and electricity to the households of local community. Taking the annual electricity consumption of every household in UK as 3332 KWh (“Typical Domestic Consumption Values,” 2015) and annual heat consumption as 12000 KWh (Wilson et al., 2013) total generated heat and electricity from the facility described in this study will meet electricity demand of 2737 households and heat demand of 926 households. Assuming four households in a building on average, it is found that around 230 building’s total heat and electricity demand can be meet from this facility. That means all the operating energy demand of those buildings will be supplied from the renewable source which ensure the goal of NZEB. After achieving goal of NZEB excess heat and electricity can be sold to local community or national grid according to the policy of FiT.

Depending on the amount of biogas yield the amount of heat and electricity generation will vary. Higher yields will result higher energy generation and higher number of NZEB coverage and greater revenue and lower biogas yields will result lower achievement. Another important thing is the energy efficiency of the building. Energy efficiency will ensure lower heat and electricity demand of the building which lead to achieve a greater number of NZEB with the same amount of renewable energy of same capacity installation. For making decisions regarding NZEB supported by AD of food waste or other bio-energy based technology it is required to analyse the environmental results and economic results of the chosen technology which will be helpful for policy makers to take decisions of achieving NZEB goal using bioenergy from AD of food. In the followings sections these things will be discussed.

**2.2 LCA result analysis (Environmental)**

LCA result is examined by three impact categories. These are global warming potential (GWP), acidification potential (AP) and particulate matter formation (PMF). LCA result will be analysed for a functional unit. Functional unit is assumed for treating of 1-ton food waste in AD- CHP facility. Every functional unit produces 364.45 KWh electricity, 445.32 KWh heat and 500 Kg of digestate. Environmental impacts for impact categories of GWP, AP and PMF for generation of said amount of electricity, heat and digestate is estimated. Simultaneously same impact categories are also estimated to produce same amount of heat, electricity and digestate by conventional method. By comparing these two results environmental impact for using AD-CHP facility using food waste could be identified easily.

Emissions associated with AD-CHP facility includes waste collection and transport system, fugitive emissions from AD plant, emissions from burning biogas in CHP plant, emissions from digestate application. Emissions from waste collection and transport system is calculated using model described at section 3.2 and assumptions made in section 3.3.3.2. As the diesel requirements for every ton of waste collection is taken as 10.1 litres and emissions from every litre diesel burning in truck is taken from table 03. Using these data and assumptions estimated GWP is 26.55 kgCO2eq, AP is 0.12 kgSO2eq and PMF is 0.152 kgPM10eq. Emissions from AD-CHP facility consists of biogenic CO2 emission and CH4 emission. As the GWP of biogenic CO2 is taken as 0, impacts of biogenic CO2 is not considered for GWP calculation. Using data and characterisation factor from table 04 and 02, GWP from AD-CHP facility for 1 ton of food waste is 124.96 kgCO2eq. AP and PMF from AD-CHP facility are 0.44 kgSO2eq and 0.163 kgPM10eq respectively. Now all these environmental impacts are estimated for digestate application from a functional unit. It is found that the GWP potential for digestate application of a functional unit is 49.45 kgCO2eq, AP is 0.013 kgSO2eq and PMF is 0.0122 kg PM10.

Same environmental impacts are calculated to produce same amount of electricity, heat and digestate using conventional method of fossil fuel. Using assumptions made in table 05, GWP for 364.45 KWh electricity and 445.32 KWh of heat is 294.36 kgCO2eq. AP and PMF for producing same amount of energy is 0.45 kgSO2eq and 0.26 PM10eq respectively. In section 3.3.3.5 it is estimated that the same amount fertilizer produced from every functional unit of waste requires GWP of 72.32 kgCO2eq if these are produced by conventional procedure. To investigate the environmental sustainability of AD-CHP facility in replacement of conventional system of energy and fertilizer production from a functional unit, resultant GWP, AP and PMF are illustrated in the following figure:

Figure 04: GWP of AD-CHP and avoided emission for same amount of energy and fertilizer.

From the above figure, the GWP for same amount energy and fertilizer is significantly lower for AD-CHP system in comparison with conventional system. AD-CHP system saves around 165.72 kgCO2eq for same amount of energy and digestate otherwise generated by conventional system. This ensures that the AD-CHP system using food waste is environmentally more sustainable than the conventional system in the terms of GWP.

Comparison of AP between emissions from AD-CHP and avoided emissions is as like as:

Figure 05: AP of AD-CHP, avoided emission and resultant

AP of AD-CHP system is a bit higher than the conventional system for the same amount of heat, electricity and digestate. This could be due to the fugitive emissions from the facility. Special care and use of technology to reduce emission is required to rectify this issue.

Particulate matter formation (PMF) from AD-CHP, avoided emission and resultant emissions are illustrated as:

Figure 06: PMF of AD-CHP, avoided emission and resultant emission

**2.3 Economic Result Analysis**

Economic analysis is carried out by analysing the project’s NPV. NPV calculation requires the net present values of all the costs and revenues. Costs includes the capital cost (Capex) and operation cost (Opex). As per assumptions in section 3.4.1 capital cost of the plant is £ 4.5 million. Yearly operation cost (Opex) consists feedstock cost and plant operation cost. According to the assumptions of section 3.4.2 yearly Opex is £ 1.2 million. Yearly electricity and heat generation from AD-CHP facility is 9111250 KWh and 11133000 KWh respectively. Heat and electricity are used to meet the demand of NZEB and eventually it will save the cost of heat and electricity to purchase from national grid. The rate from national grid is mentioned in section 3.4.3. Annual income from heat and electricity are £ 1.31 million and £ 0.42 million respectively. Annual income from digestate as per rate mentioned in section 3.4.4 is £ 0.163 million. Another significant income source of AD plant is tipping fee. Annual income from tipping fee is £ 0.725 million. Total cost and revenues from the facility is summarised in the following table:

|  |  |
| --- | --- |
| Costs / Revenues | Amount (£) |
| Capex | 4.5 million |
| Opex (yearly) | 1.2 million |
| Heat, electricity, digestate (yearly) | 1.893 million |
| Tipping fee (yearly) | 0.725 million |

Total yearly cost is £ 1.2 million, and revenue is £ 2.618 million which gives yearly net income £ 1.418 million. 20 years cash flow diagram is as like as:

Figure 07: Cash flow diagram of the project (supply to NZEB)

Taking the lifetime of the plant as 20 years and discount rate as 6%, according to equation (i)

NPV = -4.5 + $\frac{1.418}{0.06}$ {1-$ \frac{1}{\left(1+0.06\right)^{20}}$} = £ 11.76 million

Positive NPV value indicates that the project is economically feasible.

In case of supplying heat and electricity to the national grid as per FiT scheme rate yearly net revenue becomes £ 0.258 million (details given in appendix B). Considering this situation cash flow diagram becomes:

Figure 08: Cash flow diagram (selling heat and electricity at FiT rate)

For 20 years period and 6% discount rate NPV for this cash flow is – £ 1.54 million which informs that the project is not economically viable when it sells heat and electricity at the rate of FiT.

Taking carbon credit as a source of income according to section 3.4.6 every ton of food waste save CO2 emissions 165.72 kgCO2eq and yearly saving is 4143 tonnes CO2eq. Annual revenues from this carbon saving is £ 0.207 million. Using heat and electricity for NZEB yearly net revenue found as £ 1.626 million (detail calculation in appendix C) and cash flow diagram becomes:

Figure 09: Cash flow diagram with carbon credit and supply energy to NZEB with carbon credit

This cash flow diagram gives NPV with 20 years period and 6% discount rate as £ 14.34 million which informs that the project is economically more viable with considering carbon credit as income when supplies heat and electricity to fulfil NZEB goal.

Adding income from carbon credit is included with the cash flow when AD-CHP facility supply heat and electricity at the rate of FiT yearly net revenue converts to £ 0.46 million (detail calculation given in appendix D), the cash flow diagram turns into

Figure 10: Cashflow diagram with carbon credit (heat and electricity at FiT with carbon credit)

This cashflow provides NPV with the same period and discount rate as £ 0.78 million. NPV is now positive with FiT rate which indicates this project is economically feasible. At the previous calculation NPV was negative with FiT rate, considering carbon credit NPV becomes positive with the FiT rate. This project is economically feasible in both cases of supplying heat and electricity for both NZEB and to national grid at FiT rate while considering carbon credit as income.

It is clear from the above discussion and illustration that NZEB using AD-CHP is economically feasible at all cases when heat and electricity are used for net zero energy building. Using energy for NZEB saves a significant amount of money as purchasing energy from national grid is costlier than the rate of selling heat and electricity at FiT rate. Savings are higher as NZEB does not require purchasing heat and electricity from national grid. Among all the scenarios investigated for economic feasibility, only selling heat and electricity at FiT rate without carbon credit is not economically viable. All other arrangements are economically feasible. However, incomes from tipping fees and carbon credit are also a potential source of income to motivate investor to introduce NZEB using AD-CHP installation.

**SDG Implementation with this Research**

This study found that the Net Zero Energy Building supported by bioenergy is economically as well as environmentally sustainable. Governments worldwide are committed to achieving SDGs. As the building is responsible for 40% of energy consumption and 36% of CO2 emission, bioenergy supported building will play significant role to provide clean and affordable energy to the building of urban areas which will help to implement goal 7 of SDG. Moreover, as this system generates energy from the waste of the urban areas which directly indicates a sustainable waste management of a city and this ensures sustainable cities and communities leading to the implementation of SDG goal 11 aimed at “making cities and [human settlements](https://www.sciencedirect.com/topics/social-sciences/human-settlements) inclusive, safe, resilient and sustainable”. In addition to that energy supplied to the NZEB using bioenergy will reduce emission of CO2 to the environment which indicates that bioenergy supported building play significant role for decarbonization which will help to limit the global temperature rise well below 20C meaning the implementation of SDG goal 13 (climate action) that calls for “urgent action to combat climate change and its impacts.

**Practical Implication and utilization of this study for the development of our country**

Power sector development is a precondition to the path of developed Bangladesh. Numerous initiatives have been taken for producing more electricity to meet the increasing demand. At present the installed capacity of the power generation is 24982 MW. Most of this power generation is based on natural gas, coal and other fossil fuels. The portion of renewable energy is very insignificant in our country. To meet the increasing demand of energy as well as to ensure sustainable development of our country it is very important to increase the share of renewable energy in the power sector. According to the power sector master plan (PSMP) 2016 the projection of power generation is 40000 MW by 2030 and 60000 MW by 2041. For achieving SDG goal 7 it is required to ensure access to affordable, reliable, sustainable and modern energy for all. A significant portion of the power generation by 2030 should be from renewable sources.

This study has analysed the economic feasibility and environmental impact of bioenergy in supporting net zero energy building. It has been clear that the energy supply from bioenergy is economically as well as environmentally sustainable. Energy supply to the buildings in urban areas like the mega city Dhaka or Chattogram using this method could be a good option to achieve SDG goal 7 as the energy generation from food waste is a renewable source. This system is environment friendly as the waste management system has not been well organised yet in our country. Waste management system would be systematic in the mega cities and this will ensure sustainable cities and communities in our country leading to the achievement of SDG goal 11. In addition to that the target of reducing CO2 emission will be achieved as the fossil fuel used will be reduced.

It is clear from the above explanation that this study could play a significant role to achieve different SDG goals as well as to ensure sustainable development of our country.