



**An-Najah National University**  
**Faculty of Graduate Studies**

**INTEGRATED PV-BIOGAS SYSTEMS  
FOR POULTRY FARMING: OPTIMIZING  
ELECTRICITY AND HEAT PRODUCTION**

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of Master of Clean Energy Engineering & Conservation of Consumption, Faculty  
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## **Dedication**

To my beloved parents,

To my dear brother and sisters,

To my friends and supportive colleagues,

To my esteemed teachers and doctors, whose guidance and care have been invaluable,

To everyone who stood by me, offering unwavering academic and moral support,

To all who wished for my success,

To everyone who stood by me with kindness, patience, and faith,

This work is dedicated to you.

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For my first and greatest supporters—my mother and father; to my loving and supportive brother and sisters; to my dear friends for their kindness and cooperation.

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## **Abstract**

In response to the growing demand for sustainable and decentralized energy systems in agricultural regions, this study investigates the feasibility of a hybrid renewable energy system combining biogas, photovoltaics (PV), and battery storage to supply the energy needs of a farm in the Jordan Valley, Palestine. Four system configurations were evaluated in terms of technical performance, economic viability, and environmental impact.

Among the evaluated options, Scenario 4 demonstrated the most balanced performance, with the lowest levelized cost of energy (LCOE) at \$0.161/kWh, a net present cost (NPC) of \$286,212, annual energy savings of \$84,708, and a payback period of just 2.3 years. It also achieved CO<sub>2</sub> mitigation of 59.28 tCO<sub>2</sub> /year and integrated biogas use effectively, supporting both waste management and clean energy production.

In contrast, Scenarios 1, 2, and 3 exhibited varying trade-offs. Scenario 1 had the highest CO<sub>2</sub> mitigation (101.1 tCO<sub>2</sub> /year) due to its reliance on PV and battery storage, but also the highest LCOE (\$0.32/kWh) and capital cost (\$347,603), making it the least economical. Scenario 2 and Scenario 3 utilized biogas more effectively and offered better waste management benefits. However, despite higher CO<sub>2</sub> emissions, their economic indicators were less favorable than Scenario 4, with Scenario 2 showing an LCOE of \$0.348/kWh and Scenario 3 at \$0.117/kWh, along with payback periods of 4.2 and 2.4 years, respectively.

Based on a multi-criteria decision analysis (MCDA), which included factors like capital investment, energy cost, environmental impact, reliability, and waste conversion, Scenario 4 scored the highest overall, confirming its superiority in delivering sustainable and cost-effective energy for remote farms.

This study emphasizes that integrated renewable energy systems, particularly those combining PV and biogas, offer a practical and scalable solution for off-grid energy needs. It supports energy independence, reduces fossil fuel dependence, and enhances environmental sustainability in rural agricultural contexts.

**Keywords:** Hybrid Renewable Energy; Biogas; Photovoltaic (PV); Battery Storage; Poultry Farms; Energy Optimization; Off-Grid Systems; Palestine; Sustainability; Waste-to-Energy.

# Chapter One

## Introduction

### 1.1 Introduction

Recently, due to the increased in population growth, industrialization, and development, the global demand for energy also increased accordingly. In general, fossil fuel power plant has become a major concern since that this source is finite, and its availability is expected to decrease over time. Also, they have a serious environmental impact due to the increasing emissions of GHG's such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), etc. These emissions greatly affect human health, contribute to global warming and climate change [1,2].

As mentioned in the International Energy Agency (IEA) that the energy sector is responsible of about three-quarters of global CO<sub>2</sub> emissions and this increase the focus on rely on renewable energy sources and reduce dependence on fossil fuels. [2], and this will contribute and reduce the impact on the climate.

Accordingly, due to the existence of such challenges, concepts such as sustainability and reliability have emerged to emphasize the need for alternative renewable sources [3]. Several studies now focus on developing more effective and resilient power solutions for rural areas, especially for off-grid systems. In addition, the concept of decentralization, which has recently become popular, promotes the generation and distribution of energy close to the point of use. This approach is particularly useful for remote areas, as it enhances energy accessibility and efficiency [4].

Renewable energy sources like PV and biogas offer clean, sustainable and reliable energy solutions. These sources not only reduce gases but also enhance energy security because they rely on available resources such as sunlight and organic waste.

In areas such as Palestine, where there is a shortage of energy and a lack of reliance on energy production, the use of renewable energy alternatives becomes important, as this reduces reliance on energy imports, helps reduce costs, and contributes to the effort made to reduce climate change.

However, there are still some challenges to using alternative energy, such as technical expertise and costs. These challenges have begun to diminish with technological development and increased awareness of the environmental and economic benefits expected from using renewable energy sources.

Combining multiple energy sources such as PV and biogas has become a popular concept for obtaining an uninterrupted energy source. This combined system offers a radical and cost-effective solution [5]. There are many keys that play an important role in the effective use of these sources together. For example, the choice of site plays a major role in the effective installation of solar cells while the amount of biogas production depends on the amount of organic waste produced.

These sources play a vital role in addressing energy challenges because they rely on inexhaustible natural resources, and these systems provide significant environmental, economic and social benefits. In addition, hybridization of multiple renewable energy sources has become a widely adopted approach, providing improved efficiency and greater benefits [5].

PV systems that convert sunlight into energy through solar power plants cover applications from small to large installations. They provide solutions for the off-grid approach, especially for areas that are not connected to the grid. In recent years, technology and development have seen the cost of solar energy systems drop dramatically, making them more accessible and widely adopted. In addition, as a zero-emission electricity source, PV systems are increasingly supporting the promotion of environmental sustainability [3].

Similarly, the most widely used method for consuming waste is through the production of biogas by anaerobic digestion, which is a safe, renewable and clean energy source [5]. This process involves the decomposition of organic carbon by bacteria in an oxygen-free environment [6], producing gases such as methane ( $\text{CH}_4$ ), carbon dioxide ( $\text{CO}_2$ ), hydrogen sulfide ( $\text{H}_2\text{S}$ ), and small amounts of other gases [7]. The resulting biomass can be used as fertilizer [8]. Several parameters must be implemented, including total solids, volatile matter, pH, phosphorus, calcium, ammonia, as well as temperature and humidity. This factor has a significant impact on biogas production

[9,10] and it is important to evaluate the economic and environmental impacts of these applications for continued sustainability and effectiveness.

As for the remote farms that are not connected to the grid, producing energy to meet daily needs is a problem that needs to be solved. Extending the grid to such sites requires a large cost, and some areas, for example, in Palestine, do not allow for the electricity grid to extend there, and this poses a challenge to the owners of these farms, such as cow and poultry farms, which are usually far from residential areas.

Accordingly, renewable energy sources are the only and optimal solution for energy production for such farms. The type of renewable energy recommended to be used depends mainly on the location of the farm and the available capabilities for energy production.

## **1.2 literature review**

The concept of hybrid renewable energy has been widely studied. One study examined a hybrid system combining a 1 kW solar PV) plant with battery backup and a 3.5 kVA biogas generator, showing that the PV system handles low loads efficiently, while the biogas generator meets higher demand. The analysis confirms the economic viability of the system with a competitive cost of energy (COE) of around \$0.08 per kWh and the potential to reduce CO<sub>2</sub> emissions by 60% compared to a grid system or diesel generator [5]. Another study combined biomass and PV, using a 1.4 kVA spark ignition generator powered by raw biogas. Despite a 32% reduction in energy compared to LPG, at a cost of \$0.05 per kWh it reduces CO emissions by 50% and hydrocarbons by 40% [7].

In addition, another study develops an optimal hybrid system with solar, biogas, hydropower and battery storage to power a village in Tangi, Northwest Pakistan. This system consists of 91.4 kW solar modules, 19.6 kW hydropower, 50 kW biogas generator, 36 batteries and a 60.6 kW inverter, and has an energy cost of 0.0728 \$ per kWh, significantly reducing CO<sub>2</sub> emissions by about 75% [9].

Furthermore, one study proposes a micro-grid model for cooling, heating and power (CCHP) to enhance energy efficiency and address waste-related environmental issues on farms. By utilizing biogas from animal manure to power engines, boilers and

chillers, combined with photovoltaic power generation and battery storage, the model maximizes energy production, reduces costs with an estimated energy cost of \$0.07 per kWh, and mitigates greenhouse gases (GHG) emissions by 65% [11].

In addition, a hybrid power system using solar PV and 413 kWh of biogas has been proposed when PV is insufficient [12]. In Egypt, an improved off-grid power system combining PV and biomass technologies has a nominal power of 6573 kW and 2920 kW at an energy cost of US\$0.239127/kWh [13].

Another optimal setup includes 140 kW of biomass generator and 80 kW of PV power plant to achieve an internal rate of return (IRR) of 6.13% over 12 years while providing a 20% discount in electricity prices [14].

In Tanzania, a study explores the integration of solar PV and biogas systems to address energy shortages and power instability in rural areas. A hybrid renewable energy supply system is designed for a village to meet a daily demand of 63.41 kW. The system achieves technical and economic feasibility with a net present cost of \$106,383.50 and a levelized cost of energy of \$0.1109/kWh using HOMER. The results highlight the economic and environmental benefits of rural energy production [15].

In Ghana, a study explored the use of a hybrid solar PV, biogas and battery system to provide affordable electricity to remote communities while reducing GHG emissions. Using HOMER software, the system was shown to outperform PV, diesel, batteries and diesel-only systems in terms of costs and emissions. The hybrid system achieved a levelized cost of electricity (LCOE) of 0.256 \$/kWh [16].

Also, in Pakistan, a small-scale off-grid solar and biogas power generation system is being studied to supply rural areas. The system integrates a 30kW solar PV array, a 37kW biogas generator, 64kWh of battery storage, and a 20kW inverter. After simulating the system using HOMER and RET-Screen, it is considered technically and economically viable based on the payback period 2.5 years and internal rate of return 42.7% [17].

Another study in China involves a hybrid PV/biogas/diesel/battery system to meet the electricity needs of a village. Using HOMER software, the optimal configuration includes 400 kW PV modules, a 100 kW biogas generator, 400 batteries, and a 200 kW

inverter, operating on load tracking. The net present cost of the system is 1,808,992 \$ and the energy cost is 0.24 \$/kWh, significantly reducing CO<sub>2</sub> emissions by 1,297,174 kg per year compared to a diesel-only setup [18].

In Kenya, this study optimizes a hybrid PV, biogas and energy storage system to meet the reduced national load at the lowest cost of energy. Using four years of solar data and optimization methods, the optimized system's biogas to PV ratio is 2.4:5. This demonstrates the hybrid system's superiority over anaerobic digestion as the discount rate drops to less than 8%, highlighting its cost-effectiveness and future potential for sustainable energy [19].

A study in Nigeria explores a hybrid solar PV-biogas system to address electricity challenges at an abattoir. The facility processes 25 cows per day, with HOMER simulations identifying the optimal system to meet a daily load of 164 kWh. PV provides 38% of annual production, with an equivalent energy cost of 0.236 \$/kWh and a net production cost of 92,988 \$. The costs are split 60% for PV and batteries, 25% for the biogas generator, and 15% for the converter, demonstrating its economic and environmental viability [20].

Another study, implemented in Europe, analyzes a hybrid bioenergy-PV system with a capacity of 84.5 kW for 94 houses. The optimal system is selected and evaluated using the HOMER simulation software. Performance, efficiency and cost are evaluated, demonstrating the feasibility and sustainability of the system [21].

A student housing conversion in Indonesia to 100% renewable energy was also studied using the Homer program. The optimized system consists of 7.54 kW of solar PV, a 5kW biogas generator, an 18.78 kWh battery, and a 4kW inverter. The system generates 98.13% of the electricity from solar PV and 1.87% from biogas, with an equivalent energy cost of 0.216 \$ and a net production cost of 17,769 \$. A sensitivity analysis highlights the impact of discount rates and inflation on costs [22].

An additional study in Morocco evaluated a hybrid solar/biogas/battery system for a commercial platform using Homer. The optimized setup includes 231kW of solar, a 170kW biogas generator, a 140 kW inverter, and a 201kWh battery, achieving a LCOE

of 0.280 \$/kWh and a 40% reduction in CO<sub>2</sub> emissions compared to a biogas-only system [23].

### **1.3 Research significant**

Most researchers focus on optimizing a single scenario for hybrid systems such as PV, biogas, and battery systems. This research, however, examines four scenarios aims to highlight how renewable energy integration can meet the daily demands of rural farms for poultry and cow farms in the West Bank, Palestine, where the grid is unavailable, while considering both economic and environmental impacts. The findings will aid farmers and decision-makers in their discussions, and the methodology is applicable to similar regions and climates worldwide, making it relevant for further studies across different contexts.

In Palestine, many farmers may not be aware of the opportunity to use waste to produce energy; it is estimated that around 90% are not aware of this option. However, solar PV systems are generally more popular than biogas or other renewable energy sources. This study aims to highlight the potential of biogas production, which may increase awareness and popularity of this alternative. Given the large amount of agricultural and agri-food waste generated in Palestine, biogas could provide an effective and sustainable solution for waste management and energy production.

### **1.4 Research Questions**

The following are the key research Questions:

1. What are the suitable scenarios for integrating PV, biogas, and battery systems for isolated farms in Palestine?
2. How much of the farm's daily energy demand (electrical and thermal) can be covered by each energy source?
3. What are the economic and environmental impacts of each scenario?
4. Which scenario offers the most effective solution for covering the farm's energy needs?

## 1.5 Research Objectives

As a result of this research there are many objectives that will be achieved. We can limit and define them in the many points.

The Objectives for this Thesis:

1. To propose and evaluate four energy supply scenarios integrating photovoltaic (PV), biogas, and battery systems.
2. To analyze the performance of each scenario in meeting the farm's daily energy demands and managing agricultural waste.
3. To design and size each system, and assess the economic and environmental parameters based on technical and resource-related factors.

## 1.6 Thesis Structure

This thesis is organized into [4] chapters, as shown below:

**Chapter 1:** Introduction: This chapter will introduce the research problem, literature reviews, research significant, research questions and objectives. Also, it will describe a brief description about the used methodology.

**Chapter 2:** Methodology and Scenarios Design: This chapter outlines the research framework, covering data collection, energy analysis, scenario development, design calculations, and the evaluation process using multi-criteria decision analysis (MCDA). This chapter designs Four energy scenarios combining PV, biogas, and batteries, analyzes biogas production and farm resource characteristics, and evaluates technical, economic, and environmental impacts.

**Chapter 3:** Results and Discussion: This chapter discusses the economic results, CO<sub>2</sub> production and mitigation, and bio-fertilizer benefits of the Four energy scenarios, concluding with a Multi-Criteria Decision Analysis (MCDA) to identify the optimal solution.

**Chapter 4:** Conclusion and Recommendations: This chapter summarizes the key findings, presents the optimal energy solution, and offers practical suggestions for improving farm energy systems. It also highlights areas for future research and policy recommendations, considering technological advancements and evolving energy trends.

# Chapter Two

## Methodology

### 2.1 Introduction

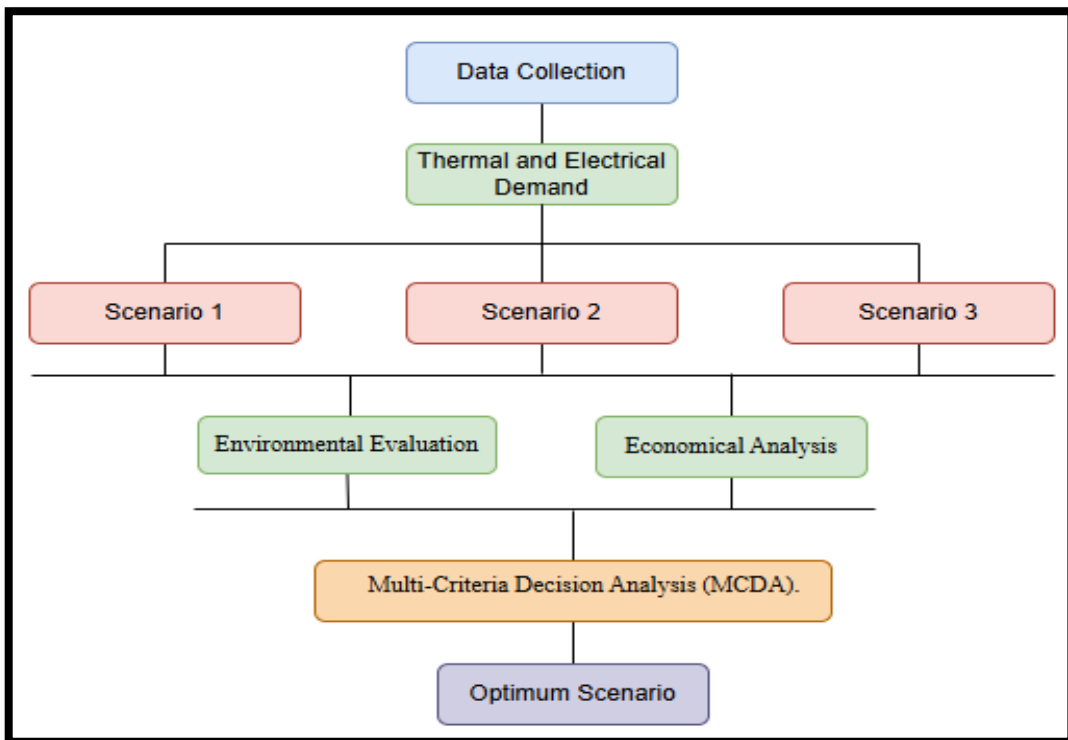
There is a two main factor for any systems design, the first one is the available resource and the other is the site demand. In this study this main key will by a critical role. For farms in rural areas, the available resources will Confine the renewable energy sources which can be used to cover the daily demand for them.

The methodology structure for this research is represented in Figure 2.1:

1. Data collection.
2. Load Study.
3. Build Scenarios.
4. Design each Scenario.
5. Cost analysis.
6. Environmental evaluation.
7. Multi-Criteria Decision Analysis (MCDA).

**Figure 2.1**

*Methodology Structure*



## **2.2 Data Collection**

The success of this research depends on having accurate and reliable data for developing the scenarios, as well as for conducting the economic and environmental evaluations. To ensure this, the data collection process followed several key steps:

### **1. Study area**

The study area refers to the geographical location where the research is conducted, including the specific characteristics of the farm being analyzed. This primarily includes solar radiation levels and available land.

### **2. Available resources**

This includes available renewable energy sources, such as solar radiation, organic waste potential, and other local energy sources. Understanding these resources helps in building each scenario and sizing energy systems.

### **3. Energy Consumption Data**

This data includes the farm's electrical and thermal energy needs, taking into account seasonal variations. Understanding energy consumption is crucial for creating a load study, as it helps identify the farm's total energy requirements and how they change throughout the year. This information will be used to size energy systems that can efficiently meet the farm's load profile.

### **4. Financial Data**

Financial data includes the costs associated with implementing and operating renewable energy systems, such as initial capital costs, operating and maintenance costs. This data is vital to conducting a cost analysis of proposed scenarios and determining their economic feasibility.

This data will be mentioned later in the economic study.

### **5. Environmental Data**

Environmental data focuses on how energy systems affect the environment. This includes factors like emissions, energy efficiency, and potential reductions in GHG's emissions from renewable sources. Such data is crucial for evaluating the environmental

benefits of different scenarios and understanding how they contribute to meeting sustainability goals. This data will be mentioned later in the Environmental Evaluation.

### **2.2.1 Study Area**

The study area for installing a photovoltaic system and its hybridization with biogas is located in Palestine - Jordan Valley (West Bank) The coordinates (latitude and longitude) are: Latitude: 32.0°N, Longitude: 35.5°E. This area has high solar radiation which makes it suitable for solar energy generation Figure A.1 in appendix A shows the Geographical location of the site. This site suffers from a lack of electricity and grid unavailability.

Based on (PVGIS ©European Union, 2001-2024) [24] as shown in the figure, the average days of peak sunshine are 5-7 hours in August as shown in Figure A.2 in appendix A, and 4-5 hours in winter which presented in Figure A.3 in appendix A.

### **2.2.2 Available Resources**

For the mentioned site, two main resources are available: sunlight and animal waste from the poultry and cow farms. These two resources will be used to cover the electrical and thermal daily demand for these farms.

#### **1. Solar Energy Resource**

This site has favorable temperatures and consistent solar radiation throughout the year, making a PV system the optimal source for electricity generation. From HOMER Software, according to site coordinates the daily temperature, with an annual average of 19.94°C, is shown in Figure A.4 in appendix A, and the daily solar radiation, averaging 5.2 kWh/m<sup>2</sup>/day, is presented in Figure A.5 in appendix A.

#### **2. Animals waste**

Poultry and cow farms generally produce a high amount of manure. The availability of this manure makes anaerobic digestion an optimal solution for biogas production.

The estimated amount of waste from each animal depends on the weight of each animal. This amount will help to find the total volatile solids which we affect the amount of produced biogas. Table B.1 in appendix B shows the daily estimated waste.

## 2.3 Load Study

A two-period load study was conducted on real poultry and cattle farms, covering the period from May to October as the first period and from November to April as the second period. During these months, the loads were almost identical. Table 2.1 shows the load data for each period.

**Table 2.1**

*Periodic Load Data for Poultry and Cow Farms*

	Period 1		Period 2	
	Electrical load (kWh)	Electrical load (kWh)	Thermal load (MJ)	
Poultry farm	331.57	277.54	451.08	
Cow Farm	290.1	280.1	129.6	
Total Loads	621.67	557.64	580.68	

- **Broiler farm**

For broiler farms, lighting represents the largest electrical load, as lights must operate 24 hours a day, in both periods.

Figure A.6 in appendix A represents the two-period loads for a broiler farm. Figure 2.2 represents the daily load curve for the two periods. During Period 1, daily electrical loads increase in the afternoon due to increased demand for ventilation and fans to maintain a constant indoor temperature. In contrast, during Period 2, electrical requirements increase in the evening due to increased heating requirements, primarily for thermal requirements.

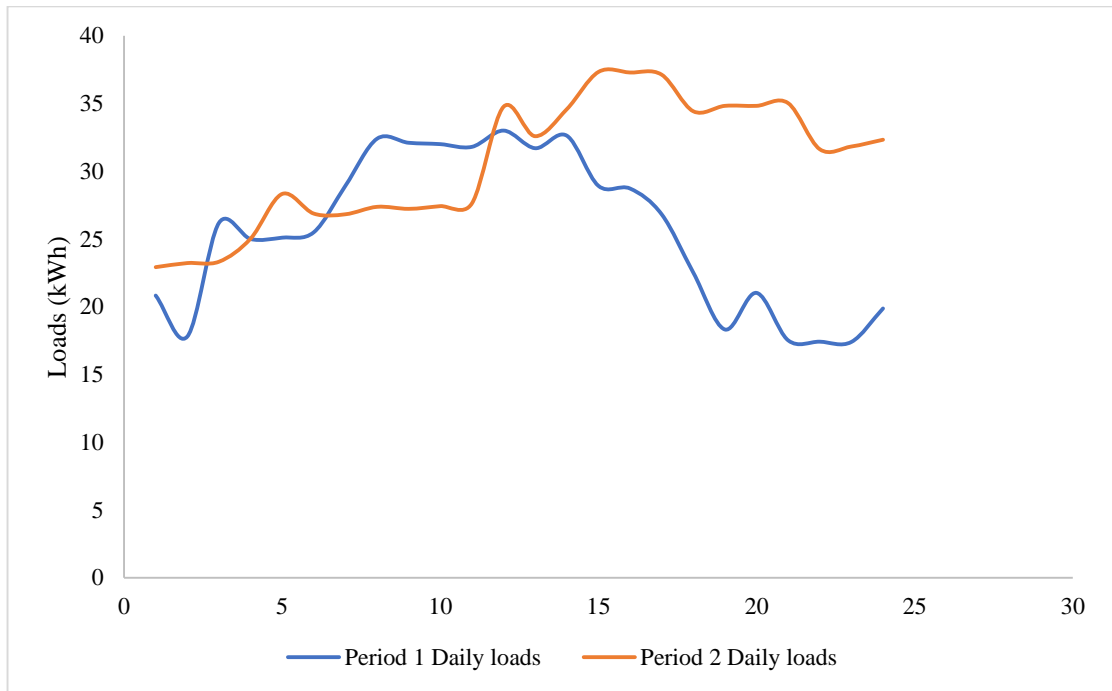
- **Cow Farm**

For a cow farm, there is not much difference between the electrical loads of the two periods except for the cooler and milking tank which is used to keep the milk at a low temperature, about 3 degrees Celsius. If the milk temperature rises, microbes and bacteria can start to grow, causing the milk to spoil. Figure A.7 in appendix A shows the loads of the two periods.

The daily demand shown in Figure 2.3 increases when the milking machine is running. The milking machine runs 3 times each day and has a vacuum pump that helps extract the milk from the cow's udder.

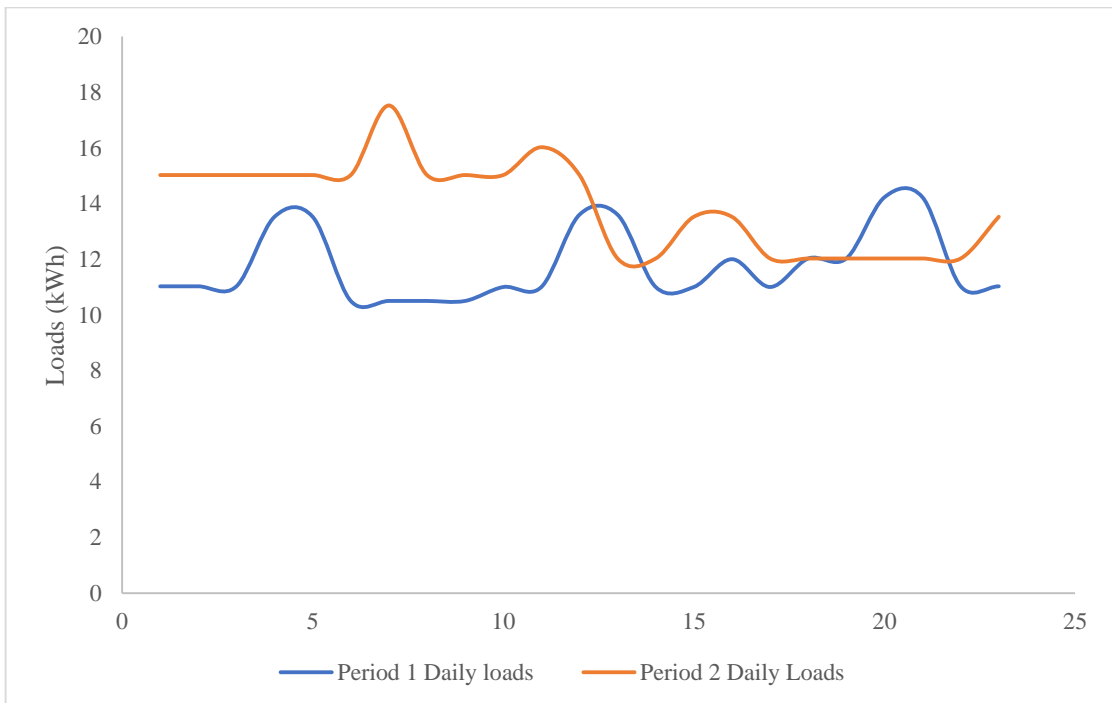
**Figure 2.2**

*Periods daily load curve for broiler farm*



**Figure 2.3**

*Periods daily load curve for Cow farm*



## 2.4 Estimated Scenarios

Based on the available resources mentioned in Section 2.2.2, Four different scenarios are built to cover the periodic load profile described in Section 2.3. These scenarios focus on the PV system, biogas energy, and battery storage. The Four studied scenarios are as follows:

**Scenario 1:** PV system studied with 75 kW peak and 2\* 2100 Ah batteries.

**Scenario 2:** In this scenario the biogas will be used to generate electricity cover 251.85 kWh of the daily load and PV system with 20 kW peak used to cover 103.54 kWh and battery system with 2800 Ah to cover the shortage. Heat recovery used to heat the water and air for the farms in winter.

**Scenario 3:** The biogas will be used to cover the thermal needs only for heating water and air in and the PV system 21 kW peak and battery system 470 kWh to cover load for 2 days of autonomy.

**Scenario 4:** In this scenario, a 16 kW PV system supplies part of the electrical demand, while the biogas system meets the thermal demand and the remaining electrical needs. A battery system is included to handle any energy shortfalls.

Each scenario is designed to optimize system efficiency, cost-effectiveness, and environmental sustainability. The systems are sized according to energy consumption data and available resources, taking into account technical, financial, and environmental factors. This results in four distinct scenarios that can be compared in terms of their economic performance and environmental impact in the next stage of analysis.

## 2.5 Design Calculations and Software

### 2.5.1 Design Calculations

This section covers the main equations and formulas used in designing renewable energy systems, estimating energy production, and calculating system size for each scenario. The following equations were fundamental in the design process and the economic and environmental assessment:

### 1. Daily digester feed

The daily feed to the digester is set with 2:1 ratio of cow manure to poultry manure, with dilution ratio of 1:1 with water is applied to the mixture. So, the total daily feed can be calculated according to equation (1):

$$\text{Total daily feed} = \text{total daily manure} + \text{amount of water} \dots\dots\dots(1)$$

### 2. Reactor volume

Reactor is where the organic material, such as manure, or other biodegradable materials, undergoes anaerobic digestion to produce biogas.

$$\text{Reactor Volume} = \frac{\text{D.F} \times \text{R.T}}{\rho} \dots\dots\dots (2)$$

Where D.F is the daily feed, R.T is retention time is the duration that the materials remain in the digester = 25 days, and density for the diluted manure which can be assumed to be 1 kg/m<sup>3</sup> (density of water).

### 3. Fixed dome digester

The fixed dome digester consists of two main sections: a cylindrical base and a hemispherical top. Therefore, the total volume of the digester can be expressed by the following equation (3):

$$\text{Total digester Volume} = \text{Volume of cylinder} + \text{Volume of Hemisphere} \dots\dots\dots (3)$$

Where:

$$\text{Volume of cylinder} = \pi r^2 h$$

$$\text{Volume of Hemisphere} = \frac{2}{3} \pi r^3$$

Where r is the radius (m) and h is the height of the digester (m).

### 4. Solar PV

The rated power for the PV depends on the daily demand needed and the peak solar radiation hours (PSR) in the study area so it can be calculated as equation (4):

$$P_{PV} = \frac{E}{\text{DSR} \times \eta} \times S.F \dots\dots\dots (4)$$

Where  $P_{pv}$  is the PV rated power (kW),  $E$  is the daily energy demand (kWh),  $PSR$  is the peak solar radiation (hours)  $\eta$  is the efficiency of the PV system and  $S.F$  is a safety factor.

## 5. Battery

To determine the required size of a battery storage system capacity (B.C.), we must take many factors in consideration and it can be calculated

using equation (5):

$$C_{Ah} = \frac{E \times DA}{DoD \times \eta \times V_B} \dots\dots\dots (5)$$

Where  $C_{Ah}$  is the battery capacity (Ah),  $E$  is the daily energy demand (kWh),  $DA$  is Days of Autonomy which is the number of days the battery should support the load without recharging,  $DoD$  is Depth of Discharge which is the maximum percentage of the battery capacity that can be used without damaging it,  $\eta$  is the efficiency of the battery and  $V_B$  is nominal value of DC voltage of the battery string.

## 6. Turbine

To determine the mechanical power required from the turbine in the first scenario it can be calculated:

$$P_{mech} = \frac{P_{elec} \times S.F}{\eta} \dots\dots\dots (6)$$

Where  $P_{mech}$  is the mechanical power for the turbine ( $kW_{mechanical}$ ),  $P_{elec}$  is the electrical power for the turbine (kW),  $S.F$  is the safety factor and  $\eta$  is the efficiency of the turbine.

The electrical power for the turbine can be calculated by the following equation:

$$P_{elec} = \frac{E_{elec}}{T} \dots\dots\dots (7)$$

Where  $P_{elec}$  is the electrical power for the turbine (kW),  $E_{elec}$  is the electrical energy (kWh),  $T$  is the time period (hour).

The generator will be driven by the turbine in scenario 1, the electrical power can be calculated as equation (8):

$$P_{elec} = P_{mech} \times \eta_{gen} \dots \dots \dots (8)$$

Where  $P_{elec}$  Is generator electrical power (kW<sub>elec</sub>),  $P_{mech}$  is the mechanical power (kW<sub>mech</sub>) and  $\eta_{gen}$  is the efficiency for the generator.

For three phase generator the current can be calculated using equation (9):

$$I_{3-phase} = \frac{P_{elec}}{\sqrt{3} \times V \times P.F.} \dots \dots \dots (9)$$

Where  $P_{elec}$  is the electrical power of the generator (kW),  $V$  is the line-line voltage (volt), P.F. is the power factor.

The synchronous Speed can be calculated as equation (10):

$$n_{sync} = \frac{120 \times f}{p} \dots \dots \dots (10)$$

Where  $n_{sync}$  is the synchronous speed (rpm),  $f$  is the frequency (Hz) and  $p$  is the number of poles.

## 7. Pump

Pump rated shaft power can be calculated according to equation (11) [35]:

$$P_{pump} = \frac{\rho \times g \times H \times q}{\eta} \dots \dots \dots (11)$$

Where  $P_{pump}$  is the power rated for the pump (kW),  $\rho$  is density for water (kg/m<sup>3</sup>),  $g$  is the gravitational acceleration (m/sec<sup>2</sup>),  $H$  is pump head (m),  $\eta$  is the efficiency for the pump and  $q$  is the volumetric flow rate (m<sup>3</sup>/s).

## 8. Cooling/Heating system

For both the cooling systems like absorption chiller and heating system like heat exchanger the equations can be used following:

Rate of heat transfer during a phase change

$$Q = \dot{m} \times h_{fg} \dots \dots \dots (12)$$

Where  $Q$  is Heat transfer rate (in Watts, W or J/s), representing the energy transferred per unit time,  $\dot{m}$  is mass flow rate (in kg/s) and  $h_{fg}$  is the latent heat of vaporization or condensation (in J/kg).

Mass flow rate

$$\dot{m} = \frac{Q}{C_p \times \Delta T} \dots\dots\dots (13)$$

Where  $\dot{m}$  is mass flow rate (in kg/s),  $Q$  is Heat transfer rate (in Watts, W or J/s),  $C_p$  is the specific heat capacity of the fluid at constant pressure (in J/(kg·K)),  $\Delta T$  is the temperature difference (in K or °C) between the inlet and outlet.

### 9. economical calculation

Cost of energy

The annual cost of energy COE represents the total cost to generate a unit of energy, it accounts for all capital, operational, and maintenance costs divided by the total energy produced or utilized over the system's lifetime.

$$COE = \frac{C_a}{E_a} \dots\dots\dots (14)$$

Where  $C_a$  is the annual cost (\$) and  $E_a$  is the annual energy production (kWh).

Energy Saving

The Energy Savings E.S equation calculates the financial benefit of using an alternative energy system compared to grid electricity, defined as:

$$E.S = (GC - SC) \times E_a \dots\dots\dots (15)$$

Where GC is the grid price (\$/kWh), SC is the system cost (\$/kWh) and  $E_a$  is the annual energy production (kWh). This shows the yearly cost reduction achieved by switching from grid electricity to the designed energy system.

### Net present value

The Net Present Value NPV measures the profitability of an investment by calculating the difference between the present value of cash inflows and outflows over the system lifetime. It is calculated as:

$$NPV = \sum_{t=1}^n \frac{C_t}{(1+i)^t} \dots\dots\dots (16)$$

Where n is the system lifetime,  $C_t$  is the net cash flow at specific t, I is the discount rate.

### Payback period

The payback period PP is the duration required to recoup the initial cost of an investment.

$$PP = \frac{I}{S} \dots\dots\dots (17)$$

Where I is the system initial investment (\$) and S is the savings (\$/year).

## 10. Environmental calculation

### CO<sub>2</sub> produced

The amount of CO<sub>2</sub> produced from any source can be calculated using equation 18:

$$CO_2 = EF \times E \dots\dots\dots (18)$$

Where EF is the emission factor and E is the energy produced from the source.

### CO<sub>2</sub> mitigation

The CO<sub>2</sub> mitigation  $\Delta CO_2$  from renewable sources can be calculated using the following formula:

$$\Delta CO_2 = EF_{FF} \times E - EF_{RE} \times E \dots\dots\dots (19)$$

Where  $EF_{FF}$  is the emission factor from fossil fuel, E is the energy produced from renewable energy and  $EF_{RE}$  is the emission factor from Renewable energy.

## **2.5.2 Software and tools**

The design and analysis of the energy systems in this study were carried out using primary tools: HOMER Pro. These tools were essential for modeling, optimizing, and evaluating the performance of each scenario.

### **1. HOMER Pro**

HOMER (Hybrid Optimization of Multiple Energy Resources) Pro is rich software used to design and optimize micro-grids by integrating renewable energy systems like solar, biogas, and battery storage. HOMER Pro helps model various system configurations, assess different sizing options, and compare the economic and environmental performance of different scenarios. In this research, HOMER Pro was used to model energy production, optimize system sizing, and evaluate the economic performance of each scenario. This was done by considering factors such as energy demand, system costs, and resource availability.

### **2. draw.io**

Draw.io was used to create visual diagrams of the energy system structures and configurations for each scenario. These diagrams offered clear, intuitive representations of the system components, such as the integration of PV, biogas, and battery systems, helping to effectively communicate the designs and configurations of each scenario in the research.

Together, these tools provide the computational, analytical and visual support needed to evaluate and optimize proposed energy solutions.

## **2.6 Evaluation Criteria**

Evaluation criteria are one of the most important factors in this research, as they will help in choosing the optimal scenario based on several economic and environmental factors in particular.

### **1. Economic feasibility**

There are several indicators for economic feasibility that were considered in this study for each scenario, as follows:

- Capital Cost: which the initial investment for the whole system in each scenario.
- Operating and Maintenance Cost (O&M): it is the operating the maintenance cost for each equipment in the systems over its lifetime.
- Net Present Value (NPV): The difference over a project's life cycle between the present value of cash inflows (savings) and outflows (investment and operating costs).
- Levelized Cost of Energy (LCOE): it shows the cost per energy produced by the system (\$/kWh).
- Payback Period: Payback Period: The time required to recover the initial investment.

## **2. Environmental Impact**

In this research the environmental impact was evaluated depend on the following factors:

1. CO<sub>2</sub> Produced: This factor evaluates the total amount of CO<sub>2</sub> emissions produced by the energy system throughout its entire life cycle.
2. CO<sub>2</sub> Mitigation: This measures the ability of the power system to reduce the CO<sub>2</sub> emissions compared to conventional power sources (like diesel or grid electricity)
3. Fertilizer: In this research, there are two options for obtaining fertilizer: using the manure directly or using the bio-fertilizer produced from the anaerobic digestion process.

## **3. System Performance**

This criterion based on two main factors:

1. Reliability: Reliability refers to the ability of a system to consistently meet the farm's energy demand without failure or downtime.
2. Ease of Implementation: This standard evaluates the practical considerations related to the difficulty of building and operating power systems.

### **2.7 Multi-Criteria Decision Analysis (MCDA) Process**

MCDA is a valuable method for evaluating and comparing different scenarios, particularly when selecting the best option is challenging due to the involvement of multiple factors.

To apply this process as mentioned in Figure A.8 appendix A, several steps need to be followed:

1. Defining Evaluation Factors: these factors were described in section 2.6.
2. Scoring: Each scenario will be given a rating for each criterion.
3. Weighting the Criteria: Each defined criterion is assigned a weight based on its relative importance.
4. Summing Results: Each score is multiplied by the weight of its respective criterion, and these values are summed for each scenario.
5. Choosing the Optimum Scenario: The scenario with the highest result is identified as the optimum choice.

## **2.8 Scenarios Design**

In this section, the design of the four scenarios explored in this research will be presented. These scenarios incorporate renewable energy sources, such as solar PV and biogas, along with an energy storage solution, such as batteries to the farms electrical and thermal energy demand.

The scenarios are created based on available resources, energy consumption patterns, financial considerations, and environmental impact.

This chapter outlines the reasoning behind each scenario, the assumptions made during their development, and the design criteria for the integrated systems. The aim is to assess the feasibility of each scenario, considering factors like cost-effectiveness, reliability, and environmental impact.

### **2.8.1 Case Study**

For a farm with 50 cows and 10,000 chickens, the estimated daily slurry production is approximately 0.6345 tons from the cows and 0.41 tons from the chickens, total daily manure 0.9515 tons/day.

Typically, broiler chickens' manure is cleared away at the cycle's end. And the manure produced by the cows is typically collected every two months. So, the manure will be collected each 35 days. The manure will be store in storage tank to be used for biogas production.

Table B.2 in appendix B shows a summary for the farm size and the daily estimated waste produced.

### **2.8.2 Farms conditions**

In this research the study is on closed Broiler farms and cow farms. For Closed poultry farms have unique conditions that require accurate data collection. Field visits to multiple farms in Palestine were essential to collect accurate and comprehensive data on their operating principles, living conditions and specific needs. These visits and this approach will ensure a better understanding of the challenges and requirements faced by these farms.

The life cycle of broiler chickens in automated closed farms is 35 to 45 days, and is influenced by factors such as farm size, housing density and environmental conditions such as temperature and humidity. Modern farms automate the regulation of these parameters, with the required temperature dropping by 0.3°C per day, starting at 34°C and dropping by 0.3°C per day to reach 22°C by day 35, while maintaining humidity levels between 50-60%, with a maximum of 80%.

On the other hand, cattle farms do not require special conditions for cattle. One important element in cattle farms is the use of large fans that operate 24 hours a day, all year round. These fans are essential for drying the soil under the cows to prevent the spread of diseases in their udders all year round. Additionally, they are essential in the summer to help cool the environment.

## **2.9 Scenarios Overview**

### **2.9.1 Scenario 1: PV-Battery system**

In this scenario, a PV system with battery backup will be used to meet all energy needs. The battery system plays a key role in covering energy loads when sunlight is not available.

Key Features:

1. PV System: The PV system will meet all electrical and thermal demands, with the thermal demand being covered electrically.

2. Battery System: The battery system will cover the loads during periods of PV production shortages, such as during winter days.

### **2.9.2 Scenario 2: Biogas, PV and Battery system for thermal and electrical demand**

In this scenario, the biogas produced will be used entirely to meet electrical demand and for heat recovery to cover thermal needs. The PV system will supply the remaining electrical demand, and the battery system will cover any energy shortages.

Key Features:

1. PV System: To meet part of the electrical demand.
2. Biogas System: To cover the remaining electrical demand.
3. Battery System: To cover any energy shortages.

### **2.9.3 Scenario 3: Biogas for thermal demand and PV/Battery system for electrical demand**

In this scenario, the thermal demand will be met by the biogas, while the electrical demand will be covered by the PV system. The battery system will address any energy shortages.

Key Features:

1. PV System: To meet part of the electrical demand.
2. Biogas System: To cover the thermal demand and any remaining electrical demand.
3. Battery System: To cover any energy shortages.

### **2.9.4 Scenario 4: Biogas for electrical and thermal demand and PV/Battery system for other electrical demand**

In this scenario, the thermal demand and some of electrical demand will be met by the biogas, while the other electrical demand will be covered by the PV system. The battery system will address any energy shortages.

Key Features:

1. Biogas System: To cover the thermal demand and any remaining electrical demand.
2. PV System: To meet part of the electrical demand.
3. Battery System: To cover any energy shortages.

## **2.10 Anaerobic Digestion and Biogas Production**

### **2.10.1 Manures Characteristics**

The poultry and cow manures in general consist of essential nutrients such as nitrogen, potassium, and phosphorus. And they mainly consist of total solids (TS), volatile solids (VS) which greatly affects the efficiency of waste for use in energy production. In addition to the potential of hydrogen (pH) and the ratio of carbon to nitrogen.

#### **1. Total Solids**

Total solids in a waste refers to the solids content, which includes organic matter. This is usually measured as the weight of dry solids remaining after all water content has been removed. Total solids in a manure is important for determining its effectiveness for various purposes such as biogas production.

For poultry manure the total solids (TS) content is usually more than 25% [25]. And the TS content in cow manure ranges from 12% to 25% of the total manure [26].

#### **2. Volatile Solids**

Volatile solids (VS) in waste refers to the portion of total solids (TS) that can be decomposed by microorganisms during anaerobic digestion and produce gas. It consists mainly of organic materials such as carbohydrates, proteins and fats. VS is essential in biogas production because it represents the biodegradable portion of waste.

In poultry manure volatile solids (VS) making up 70-80% of the TS [6,25]. Similarly, the same percentage for cow manure which comprising 70-80% of the TS [27,28].

#### **3. pH value**

The pH level of the waste is important. The pH of the waste usually ranges from slightly acidic to slightly alkaline, depending on the type of waste and its composition. Its importance lies in the fact that it affects the availability of nutrients, microbial activity, and processes such as anaerobic digestion [29].

The pH of poultry manure typically ranges between 6 and 8.5 [26,29]. Similar to the pH of cow manure which typically ranges between 5.5 and 8 [27,28]

#### **4. Carbon – Nitrogen Ratio**

Carbon to Nitrogen ratio (C-N ratio) is essential index especially for anaerobic digestion, and when use the manure as fertilizer [7]. This ratio for poultry manure varies from 10:1 to 40:1 [26]. And for cow manure it's slightly higher usually between 20:1 and 30:1, and it has a high moisture content [2].

Nitrogen content affects the anaerobic digestion process, as high nitrogen (N) content, which reaches 3-5% of the dry matter, may cause difficulties in the process. This high nitrogen content leads to high levels of ammonia (NH<sub>3</sub>), which inhibits the activity of anaerobic microbes [6,25].

##### **2.10.2 Cow and Poultry manure characteristics**

For this study the characteristics for the cow and poultry manure is shown in table B.3 in appendix B

Table B.4 in appendix B represent the characteristics for daily cow manure since 12.6 kg/cow for farm contain 50 cows so the total manure = 630 kg.

Daily poultry manure 0.041 kg/poultry, since we have 10,000 heads so total manure = 410 kg but we need 315 kg to mix with cow manure, it's composition shown in table B.5 in appendix B.

##### **2.10.3 Anaerobic digestion process**

Waste can be effectively utilized as a renewable energy source by producing biogas through anaerobic digestion. This process is safe and sustainable, converting organic matter in the digester to produce biogas using bacteria in an oxygen-free environment [6]. During anaerobic digestion, organic matter decomposes to produce a mixture of gases, including methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S), and trace gases [7,30].

Anaerobic digestion can operate under different conditions: psychrophilic, mesophilic, and thermophilic, which mainly differ in temperature. Since temperature affects the efficiency of digestion, choosing the optimal conditions is crucial [8].

To achieve a balance between biogas production, economic feasibility and process stability, it is best to operate under mesophilic conditions, with temperatures ranging from 20°C to 40°C at pH 6.5 to 7.5 [8,31].

One of the most important factors affecting the digestion process is the hydraulic retention time, which is the length of time that the materials remain in the digester. It mainly affects the stability and efficiency of biogas production [28]. Under mesophilic conditions, it is between 10 and 40 days [32].

#### **2.10.4 Biogas characteristics**

The biogas produced is methane-rich, containing between 50% and 75% methane [11]. The higher the methane content, the more energy the biogas can produce. However, to enhance the performance of biogas, it is necessary to remove other gases produced during the process, such as carbon dioxide, hydrogen sulfide, and water vapor, which will reduce the gas yield as their concentration increases [33]. This purification can be physical or chemical and depends on the desired biogas quality and available resources [6]. The main characteristics for biogas which needed in this research presented in table B.7 in appendix B and Figure A.9 in appendix A.

#### **2.10.5 Biogas Production**

The diluted manure mixture is fed into the digester to produce biogas, where the content of total solids (TS) and volatile solids (VS) are critical factors in the biogas production process. Table B.8 represent the amount of this content in the mixed manure. And Table B.6 presents the estimated amount of biogas produced.

The daily volume of biogas produced from this amount of manure, based on the volatile solids content, is shown in Table 2.2.

The calorific value of uncleaned biogas ranges from 15 to 27 MJ/m<sup>3</sup> [35], largely depending on its methane content. Typically, biogas with a methane content of 65% has a calorific value of approximately 23 MJ/m<sup>3</sup> (6.388 kWh/m<sup>3</sup>), though biogas in general can range from 20 to 26 MJ/m<sup>3</sup> [36].

**Table 2.2***Volume of biogas produced (m<sup>3</sup>)*

	VS kg	Avg. (m <sup>3</sup> /kg VS)	Produced biogas (m <sup>3</sup> )
Poultry manure	64.45	0.55	35.4475
Cow manure	116.489	0.7	81.5423
Total			116.9898

For a daily biogas production of 116.9898 m<sup>3</sup>, the daily energy output can be calculated as 2690.7654 MJ, which is equivalent to 747.33 kWh.

### 2.10.6 Digester Size

The size of the digester depends primarily on the daily amount of manure available. For this study, a mixture of cow manure and poultry manure in a 2:1 ratio (cow manure to poultry manure) was chosen characteristics in table B.8 in appendix B, as research has shown this combination produces optimal biogas and methane under mesophilic conditions. The manure is diluted with water in a 1:1 ratio, and a retention time of 25 days is applied to ensure efficient digestion [37].

The farm generates 0.9515 tons of manure daily, which requires an equal amount of water for dilution using equation (1). This results in a total daily feed to the digester of 1.903 tons.

Total daily feed = total daily manure + amount of water

Total daily feed = 0.9515 + 0.9515 = 1.903 tons

Using Equation (2), the reactor volume was calculated to be 47.5 m<sup>3</sup>.

$$\text{Reactor Volume} = \frac{D.F \times R.T}{\rho} = \frac{1.903 \times 25}{1} = 47.5 \text{ m}^3$$

To allow for biogas production during the digestion process, an additional 50% of the digester's volume (23.75 m<sup>3</sup>) is added.

In total, the digester needs to have a volume of 71.25 m<sup>3</sup>. A fixed dome design was selected for its advantages, such as reduced gas loss due to its minimal corners and its

compatibility with local construction methods. The dimensions of the digester, calculated using Equation (3), are shown in Figure A.10 and A.11 in appendix A.

$$\text{Total digester Volume} = \text{Volume of cylinder} + \text{Volume of Hemisphere} = \pi r^2 (4) + \frac{2}{3} \pi r^3 = 2.06 \text{ m}$$

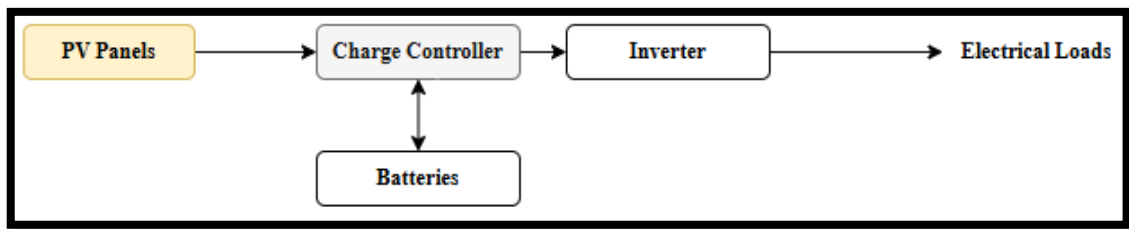
## 2.11 Technical Scenarios Design

### 2.11.1 Scenario 1

In Scenario 1, which focuses exclusively on using a PV system with battery storage Figure 2.4 represent the Schematic for this scenario, the system sizing is outlined in Table 2.3, which details the loads and the PV sizing based on equation (4).

**Figure 2.4**

*Schematic of Scenario 1*



**Table 2.3**

*Scenario 1 Sizing for PV and Battery Storage*

Period 1 loads	404.08 kWh
Period 2 loads	306.7 kWh
Avg. Peak Sun Hours	5.2 hours
PV Peak Power	75 kW
PV modules	195 modules
Battery size	2 strings each 2100Ah
Number of batteries	60 batteries/string

The PV system's peak capacity is 75 kW, requiring three inverters, each rated at 25 kW, to ensure higher reliability and efficiency. The system is designed with 5 strings, each rated at 5 kW. Using 400 W PV modules, each string consists of 13 modules, the configuration for each inverter represented in Figure A.12 in appendix A. In total, the system will require 195 PV modules. Based on equation (5), a battery storage capacity

with  $AD = 1$  day,  $DOD = 0.8$ ,  $\eta = 0.95$  and  $V_B = 120V$  so we need 2 strings each 2100 Ah. A 2100 Ah/2V battery selected; we need 60 batteries in each string, Figure A.13 in appendix A.

$$C_{Ah} = \frac{E \times DoA}{DoD \times \eta \times V_B}$$

$$C_{Ah} = \frac{390,000 \times 1}{0.8 \times 0.95 \times 120} = 4200 \text{ Ah}$$

The Monthly Contribution from the PV and the Batteries represented in Figure A.14 in appendix A. and the yearly contribution is represented in Figure A.15 in appendix A.

### 2.11.2 Scenario 2

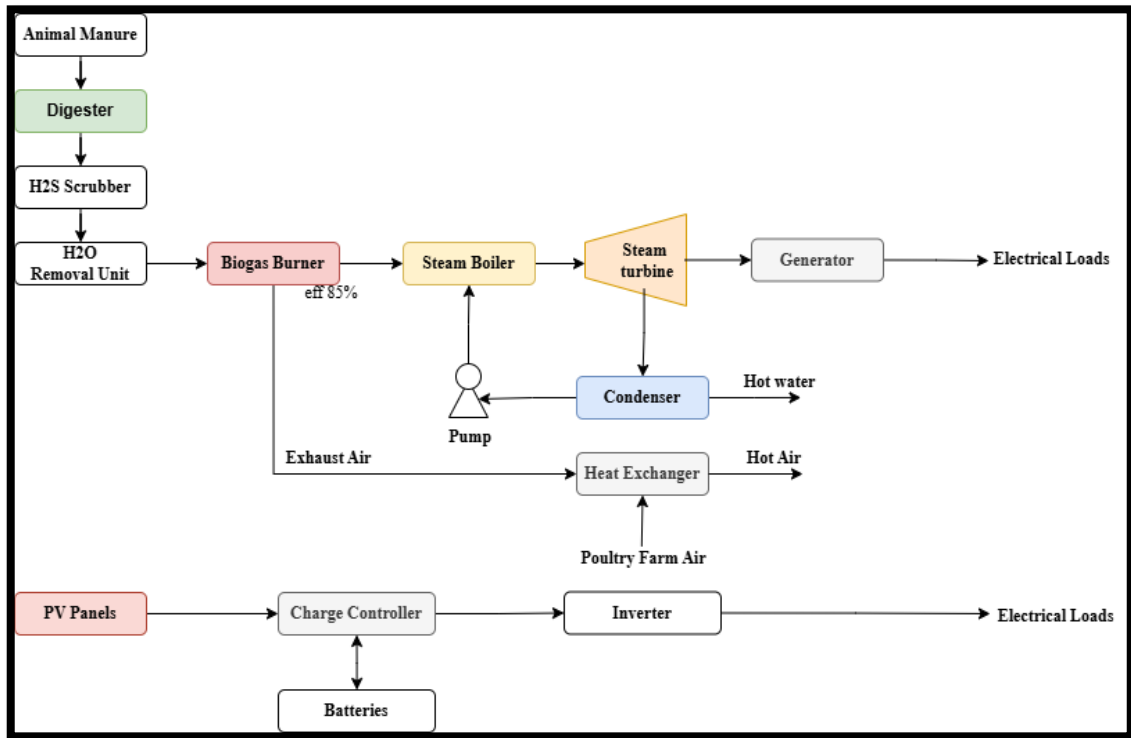
This scenario combines biogas and PV systems to efficiently manage the farm's electrical and thermal demands throughout the year. The system operates across two seasonal periods, as illustrated in Figure 2.5.

During the first period, the focus is on meeting the farm's electrical demand of 621.67 kWh. To achieve this, the biogas system is used to generate steam to drive a turbine. The turbine produces mechanical energy, which is then converted into electricity through a generator, covering the electrical load.

The PV system complements this by contributing additional electricity, and any surplus energy from PV system is stored in batteries. These batteries are essential for supplying power during nighttime or low-sunlight conditions, ensuring a reliable energy supply.

**Figure 2.5**

*Schematic of Scenario 2*



To maximize the efficiency of the system, a heat recovery process is implemented. The steam coming out of the turbine is condensed, and the remaining heat is used to heat water. Furthermore, the exhaust gases from the biogas burner are redirected to a heat exchanger, where the heat is used to warm the air. This preheated air becomes valuable in the second period, especially to support the poultry farm, demonstrating the efficiency and sustainability of the system.

During Period 2, the energy demand rises considerably, primarily due to the requirement of 580.68 MJ per day for heating water and air. This increased thermal load is efficiently met using the residual heat recovered from the condenser and heat exchanger in the biogas system.

A PV system with battery backup is used to cover the remaining electrical needs. However, since the PV system alone cannot meet the entire load in winter, battery storage becomes critical to cover for the deficit.

The purification from H<sub>2</sub>S and H<sub>2</sub>O is highly needed here since it can cause corrosion to the engine and metal components.

The recent steam boiler with biogas as a burned fuel efficiency is about 85% [38]. And overall efficiency for steam turbines it ranges from 30% - 42% [39]. The electrical efficiency of generator 90-98%, table 2.4 represent the energy contribution for each source.

**Table 2.4**

*Scenario 2 Energy Contribution and Load Distribution*

Period 1 loads	404.08 kWh
Period 2 loads	306.7 kWh
Biogas steam system efficiency	33.7%
Biogas energy Contribution	251.85 kWh
Avg. PV energy contribution	103.54 kWh
Battery size	2800Ah/48V

This system is based on a steam turbine cycle. While steam turbines are typically used in large-scale applications, this scenario was developed using a study that explored the feasibility of a small-scale steam turbine configuration. While it may not be technically feasible for practical implementation, all relevant parameters for this scenario will still be determined to allow for a comprehensive comparison with the other scenarios.

### **1. Steam turbine**

The electrical rated power can be determine using equation 6 with S.F = 1.2 finding that  $P_{elec} \approx 40$  kW.

A study had been done on 40kW steam turbine which used with bottoming cycle for testing time = 6500 hours and show isentropic efficiency up to 49% [33] which means that 49% of steam energy was converted to mechanical energy. This mechanical energy will then convert to electrical by generator with efficiency up to 95%.

A specification for specific model like 40 kW Elliott Single-Stage Condensing Steam Turbine steam inlet pressure between 10 – 30 bar and inlet pressure 200°C to 400°C (Superheated steam) with low exhaust Steam pressure and temperature about 45°C to 60°C with steam flow rate 0.5 to 1.0 ton/hour.

## 2. Generator

The generator's electrical power output is calculated by equation (7) finding that  $P_{elec} = 38$  kW. Assuming a three-phase generator operating at 400V with a power factor of 0.85, the current I<sub>3-phase</sub> is determined using equation (8) = 64.5 A.

$$I_{3-phase} = \frac{38}{\sqrt{3} \times 400 \times 0.85} = 64.5 \text{ A}$$

Additionally, for a synchronous speed with 2 poles and a 50 Hz frequency, the synchronous speed is calculated using equation (9) resulting in  $n_{sync} = 3000$  rpm.

$$n_{sync} = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

## 3. Condenser

The latent heat of condensation  $h_{fg}$  for saturated steam at temperatures between 45°C and 60°C is 2394 kJ/kg and 2357.7 kJ/kg, respectively, as obtained from thermodynamic tables [41]. For a steam flow rate of 1 ton/hour  $\dot{m} = 0.278$  kg/s, the heat transfer rate Q in the condenser is calculated using Equation (12). Substituting the values,  $Q = 660.5$  kW.

$$Q = 0.278 \times 2375.89 = 660.5 \text{ kW}$$

This is the heat the condenser needs to reject, which will then be used to heat water, raising its temperature by 15°C. The mass flow rate of the heated water is determined using Equation (13), where the specific heat capacity of water  $C_p$  is 4.186 kJ/kg°C, resulting in a water mass flow rate of 10.52 kg/s.

$$\dot{m} = \frac{660.5}{4.186 \times 15} = 10.52 \text{ kg/s}$$

## 4. Pump

The pump's rated shaft power can be determined using Equation 11, where the density of water (is 1000 kg/m<sup>3</sup>, gravitational acceleration g is 9.81 m/s<sup>2</sup>, the pump head H is 101.9 m, the flow rate  $\dot{m}$  is 0.278 kg/s, and the efficiency  $\eta$  is 70%. The pump head is calculated using  $H = P / (\rho \times g)$  [42]. At a pressure  $P = 10$  bar, the head is found to be

101.9 m. Substituting these values into the equation gives a shaft power of  $\text{Power}_{\text{pump}}=0.4 \text{ kW}$ .

$$P_{\text{pump}} = \frac{1000 \times 9.81 \times 101.9 \times 0.000278}{0.7} = 0.4 \text{ kW}$$

## 5. Heat Exchanger

The heat exchanger for heating air in a poultry farm during winter will utilize exhaust gases from the combustion process. The exhaust gas temperature ranges between 500°C and 600°C [43], with possible variations between 457 °C and 505 °C [44]. The target air temperature for the poultry farm is 85 °C most of the time. If the air temperature drops by 10 °C, it must be reheated, requiring a temperature controller to regulate the heating process effectively.

From the load study, the heat required to heat the air is approximately 6.92 kW. Using equations (12) and (13), the main parameters for the heat exchanger are summarized in Table B.9 in appendix B.

## 6. PV system

Using Equation (4), the peak power for the PV system is determined to be 20 kW. To ensure reliability and efficiency, the system requires two inverters, each rated at 10 kW. The PV system is configured with two strings; each rated at 5 kW. With a 400W PV module, the number of modules per string is calculated to be 13. Therefore, the total number of PV modules required for the system is 52, illustrated in Figure A.16 in appendix A.

Using Equation (5), the required battery storage capacity is calculated with the following parameters: autonomy days  $AD = 1$  day, depth of discharge  $DOD = 0.8$ , efficiency  $\eta = 0.95$ , and battery voltage  $V_B = 48V$ . This results in a capacity requirement of 2800 Ah. To meet this requirement, a 2800 Ah/2V battery is selected. Since the system voltage is 48V, a total of 24 batteries are required in series Figure A.17 in appendix A. Summary is shown in table B.10 in appendix B.

Figure A.18 in appendix A illustrates the monthly energy contribution from each source, showing how they collectively support the energy demands across different

periods. Also, Figure A.19 in appendix A represents the yearly contribution percentage from each source.

### 2.11.3 Scenario 3

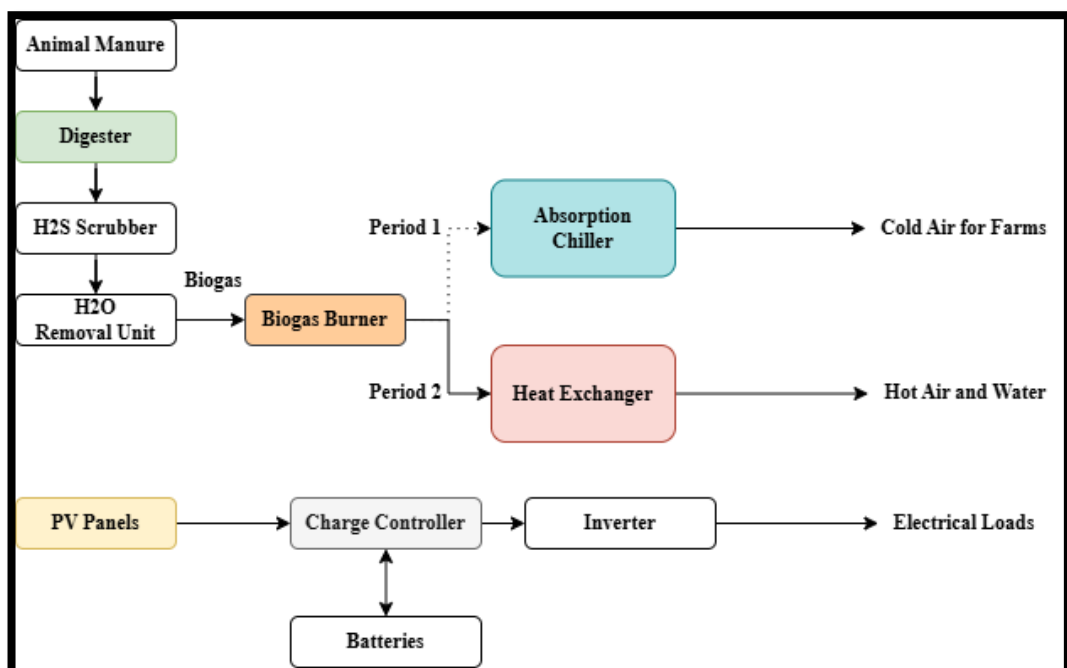
Another scenario involves integrating Biogas, PV, and Battery sources of energy to cover both thermal and electrical needs. Biogas is dedicated to directly meeting thermal needs, such as heating and cooling, while a PV system with battery storage addresses electrical demands Figure 2.6 represent the schematic for this scenario.

During Period 2, biogas is burned to provide heat for the poultry farm by warming the air and to heat water for the cow farm and domestic purposes. The PV system, with battery backup, supplies the remaining electrical loads.

Since thermal energy is available and the goal is to cool the farm, one of the most suitable and commonly used technologies to be considered is the absorption chiller. So, In Period 1, biogas is utilized for cooling through an absorption chiller, which cools the poultry and cow farms as needed. The PV system, supported by batteries, continues to handle the electrical requirements. This seasonal adjustment optimizes biogas use based on the differing thermal and cooling demands across the year.

**Figure 2.6**

*Schematic of Scenario 3*



## **1. Heat Exchanger**

In period 2, two series heat exchangers will be used to heat both water and air to increase the heat recovery from the exhaust which shown in Figure A.20 in appendix A. Plate heat exchangers are commonly used in industrial applications because it increases the surface for heat transfer [45].

Poultry farm need a hot air so stage one from the heat exchanger will be used to heat it and the exhaust from this stage enter another stage to heat water.

Stage 1 is designed to heat the air in the poultry farm. Using equations (12) and (13), the specific parameters for the heat exchanger are summarized in Table B.11 in appendix B.

The exhaust from this stage enters another stage to heat water the data for stage two in the following table B.12 in appendix B.

## **2. Absorption chiller**

In period 1, the biogas will be used for cooling using absorption chiller, most cooling systems covered by electricity however absorption chillers create a developing efficient and cost-effective sustainable solutions [48]. In biogas powered system with absorption chiller, the heat from the combustion of the biogas will drive the absorption chiller by transferring the heat to a heat transfer medium to heat water.

The heated water will be used to evaporate a refrigerant solution in the generator [49] which is mostly water with lithium bromide ( $\text{H}_2\text{O-LiBr}$ ) [48] and this is commonly used for air-conditioning [41]. The water vapor condensate with almost reject the heat for cooling water. The liquid water then passes to the low-pressure evaporator (almost vacuum), this sudden changing in pressure makes the water flash and drop in its temperature producing a cooling effect and it will be used to cool the air for cooling system. Then the water vapor absorbed back with the lithium bromide in the absorber and the cycle repeated [48,49]. All this process represented in Figure A.21 in appendix A.

One of the most important parameters in the absorption chillers is the COP with is the coefficient of performance in many studies it shows 0.7 – 0.8 most of times [50]. Also, COP is from 0.5 to 0.8 for cooling duties ranging from 2 kW to 12 kW. The rated input

temperature for the absorption chiller is  $116^{\circ}\text{C}$ , at this temperature the COP is typically 0.65 – 0.7 [41]. When the temperature drops the size and cost increase for the needed chiller [41]. The evaporation temperature ranges from  $2^{\circ}\text{C}$  -  $12^{\circ}\text{C}$  ( $5^{\circ}\text{C}$  is most common) [51]. Table B.13 in appendix B shows the details about the designed absorption system.

Based on equation (13), the evaporator and condenser can be designed. In the condenser a circulated water used for reject the heat, by taking these values as a reference its temperature increased from  $20^{\circ}\text{C}$  to  $40^{\circ}\text{C}$  for the cooling water, 11kg/h flow rate and  $115^{\circ}\text{C}$  for the vapor steam [51]. This mass flow can be also calculated from the Q needed and the enthalpy for the water at temperature  $116^{\circ}\text{C}$  using equation (12), the mass flow rate can be calculated  $\approx 11.8\text{ kg/h}$ .

Absorption chillers are generally not considered feasible for small-scale applications due to their low coefficient of performance (COP), high initial cost, and the need for a stable and continuous heat source. Additionally, their complex design, larger physical footprint, and higher maintenance requirements further limit their practicality for small-scale or off-grid settings.

#### **2.11.4 Scenario 3 improvement**

To improve energy efficiency and make better use of available resources in Scenario 3, a new configuration is suggested. In this enhanced setup, a gas turbine and generator are added to the biogas system. During the summer months (Period 1), the biogas is used to power the gas turbine, which drives a generator to produce electricity—while also capturing the heat generated for useful thermal energy. This approach allows the system to produce both power and heat at the same time, increasing overall efficiency.

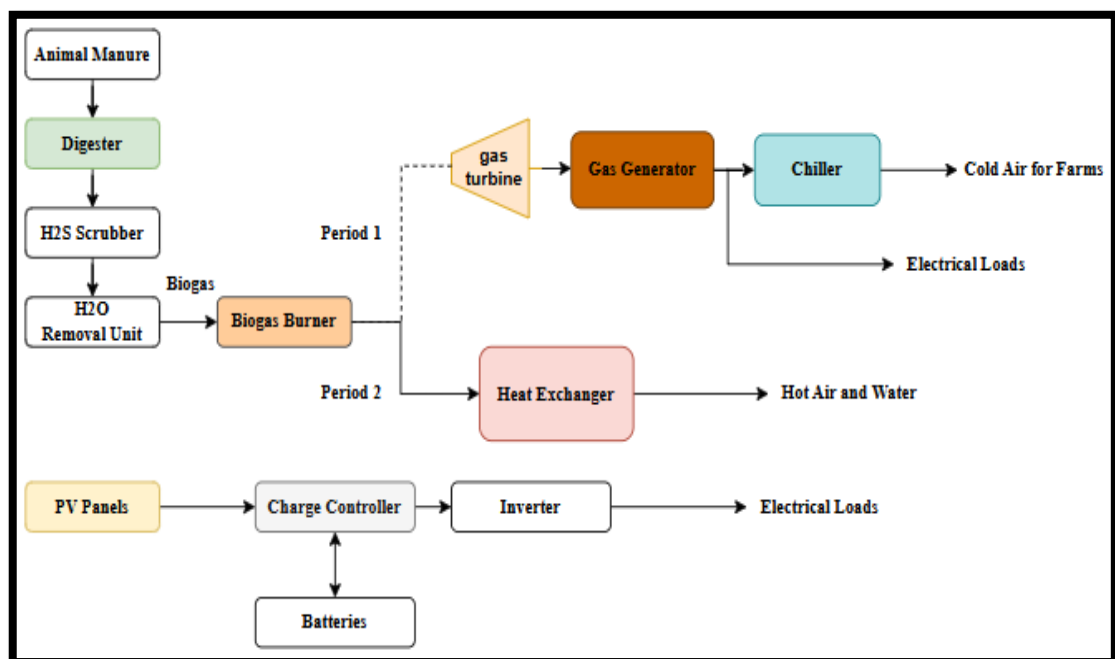
The electricity produced supports the farm's electrical demands, while the recovered heat is used to operate a vapor-compression chiller, delivering cold air for cooling purposes. This combined heat and power (CHP) strategy replaces the previously used absorption chiller, leading to a more efficient overall energy conversion.

Since the excess biogas volume of the total biogas produced in both periods amounting to 78.26% in Period 1 and 58.4% in Period 2 there is a substantial opportunity to enhance system efficiency.

The improved scenario illustrated in Figure 2.7, the excess biogas produced is redirected to cover additional electrical loads, significantly reducing energy waste and enabling a reduction in PV system size. By utilizing excess biogas for electricity generation, the system can achieve a more efficient energy balance, particularly during periods when thermal demands are lower. This adjustment not only optimizes biogas utilization but also enhances the overall efficiency and cost-effectiveness of the system, reducing dependency on PV and battery storage.

**Figure 2.7**

*Schematic of Scenario 3 improvement*



## 1. Gas Turbine

According to the improvements in this scenario, the excess biogas will be used to power a gas turbine to generate electricity. The efficiency of the turbine ranges from 30% to 42% [39]. And the COP for the chiller is almost 2.5 – 3.5. Using equations (6) and (7), the mechanical output energy can be calculated to be 299.1 kWh, given that the available energy from biogas is 747.33 kWh. The electrical output power depends on the efficiency of the generator ( $\eta=0.95$ ). Thus, the electrical output power is  $P_{elec}=12$  kW.

## **2. PV system**

With the improvement in Scenario 3, the PV system peak power requirement decreases to 50 kW. For this peak power, two inverters rated at 25 kW each are required, with five strings connected to each inverter. Each string has a capacity of 5 kW. Using 400 V PV modules, each string consists of 13 modules, Figure A.22 in appendix A. In total, 130 PV modules are needed for the system.

Based on Equation (5), the battery storage capacity is determined using the following parameters: autonomy days  $AD = 1$  day, depth of discharge  $DOD = 0.8$ , efficiency  $\eta = 0.95$ , and battery voltage  $V_B = 48V$ . The calculated capacity requirement is 450 Ah. To fulfill this requirement, a 450 Ah/2V battery is chosen. Given the system voltage of 48V, a total of 24 batteries connected in series are required which represented in Figure A.23 in appendix A.

Figure A.24 in appendix A illustrates the monthly contribution of each energy resource in Scenario 3, showing how biogas, PV, and battery systems collectively meet the electrical load demands. Figure A.25 in appendix A represents the annual electrical demand from the three sources.

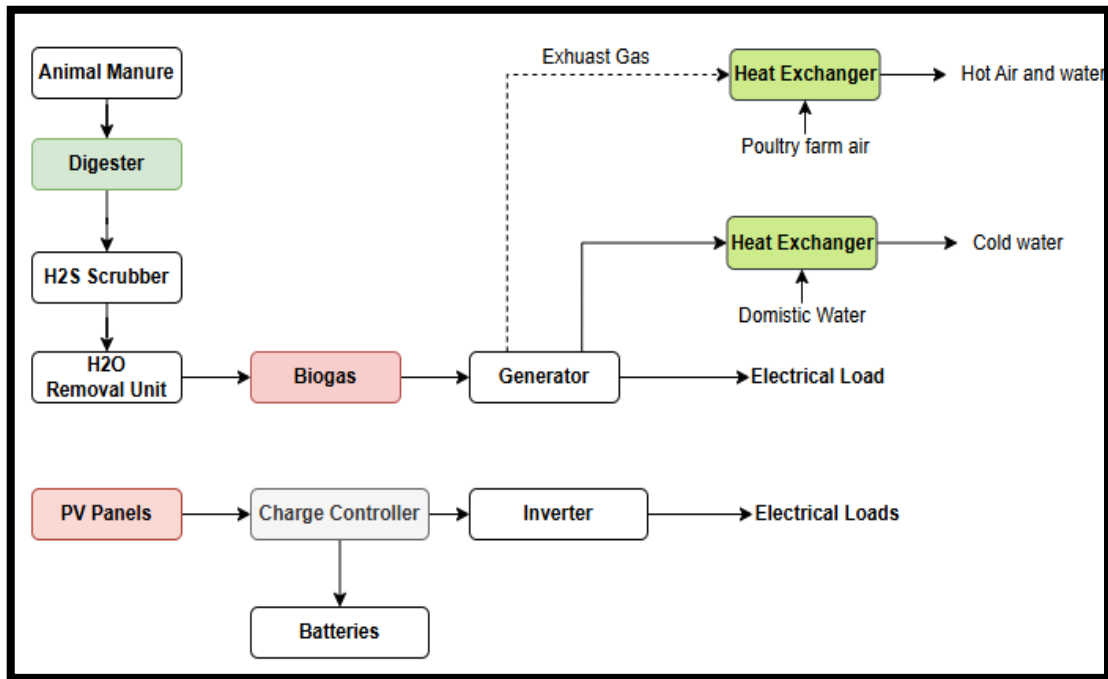
### **2.11.5 Scenario 4**

In this scenario, a biogas-powered internal combustion generator is used to produce electricity for the farm. At the same time, the heat from the engine's exhaust and cooling system is captured and reused to meet the farm's heating needs especially during the colder winter months as illustrated in Figure 2.8.

The PV system works alongside the generator by providing extra electricity, with any excess solar energy stored in batteries. These batteries play a key role in keeping the power running at night or during cloudy days, helping to ensure a steady and reliable energy supply.

**Figure 2.8**

*Schematic of Scenario 4*



The generator operates at an electrical efficiency of approximately 30% - 45 % [21], producing around 261.56 kWh/day from 116.99 m<sup>3</sup>/day of biogas. table 2.5 represent the energy contribution for each source

**Table 2.5**

*Scenario 4 Energy Contribution and Load Distribution*

Period 1 loads	404.08 kWh
Period 2 loads	306.7 kWh
Biogas energy Contribution	261.56 kWh
Avg. PV energy contribution	107.54 kWh
Battery size	1200Ah/120V

- **Biogas Generator**

A biogas generator with an internal combustion engine turns biogas from organic waste into electricity. It's a reliable and cost-effective solution, especially for farms and rural areas. On top of producing power, it can also capture heat from the engine for other uses, making the system more efficient overall.

Assuming that the generator will work for 18 hours/day, so the rated power for the generator is approximate to 15 kW.

Also, the exhaust of these generators is important since it has high temperature it around 600-625 ° C as in many specifications for these types of generators so heat exchanger to heat the air for the poultry farm in winter so it will improve the efficiency of the system. Also, the cooling system radiator water tank can be used to heat domestic water by heat exchanging so this will cool the water again to be circulate and cool the engine.

- **PV System**

Using Equation (4), the peak power for the PV system in Scenario 4 is determined to be 20 kW. To ensure both reliability and efficiency, the system is equipped with two inverters, each rated at 10 kW. The PV array is configured with two strings, each delivering 5 kW. Given that each PV module has a capacity of 400 W, the number of modules per string is 13 modules. Therefore, the total number of PV modules required for the system is: 2 strings  $\times$  13 modules = 26 modules per inverter, and for two inverters: 2  $\times$  26 = 52 PV modules in total.

Based on Equation (5), the required battery storage capacity is calculated using the following parameters: autonomy days (AD) = 1 day, depth of discharge (DOD) = 0.8, system efficiency ( $\eta$ ) = 0.95, and battery bank voltage (VB) = 48V. The resulting capacity is 450 Ah. To meet this requirement, a 450 Ah / 2V battery is selected. Since the system voltage is 48V, the number of batteries needed in series is: 48V  $\div$  2V = 24 batteries. Thus, 24 batteries connected in series are required to achieve the desired storage capacity at the specified system voltage.

Figure A.26 in Appendix A illustrates the monthly contribution of each energy source in Scenario 4, demonstrating how biogas, PV, and battery systems collaboratively meet the electrical load requirements. Figure A.27 in Appendix A presents the annual electrical demand distribution covered by these three sources.

## **2.12 Economic Data**

HOMER Software is used in this research for economical evaluation to find Net Present Value (NPV), Levelized Cost of Energy (LCOE), and payback period the data entered to HOMER will be shown in the section.

### **2.12.1 Scenario 1 data**

The HOMER data for a standalone PV system integrated with battery storage which shown in Figure A.28 in appendix A, and table B.14 in appendix B represent this data.

### **2.12.2 Scenario 2 Data**

In this scenario which hybrid PV/Biogas/Battery system. The biogas system is configured to produce electricity through the components illustrated in Figure 2.6. These components typically include a biogas digester for producing the gas, a storage tank, and Combined Heat and Power (CHP) unit that converts the biogas into electrical energy. The HOMER input data shown in Table B.15 in appendix B for the system shown in Figure A.29 in appendix A.

The biogas digester system for a fixed dome digester has associated price of 0.163 \$ per kWh [52]. According to the International Renewable Energy Agency in "RENEWABLE POWER GENERATION COSTS IN 2023," the cost for biogas production ranges from 0.05 \$ to 0.20 \$ per kWh [53]. For the steam-power production part the cost/kW = 2059.4 \$/kW [54] then the cost for this part = 21,829.64 \$.

### **2.12.3 Scenario 3 Data**

In this scenario, both PV and biogas (for thermal and electrical use) are integrated. The absorption chiller is a cost-effective and efficient solution for using biogas for cooling during the summer [48,50]. The initial cost of the H<sub>2</sub>O-LiBr single-effect absorption chiller, with a capacity of 7-11 kW and a COP of approximately 0.7, ranges from \$1,955 to \$2,350 per kW [49].

The estimated cost of installing a small-scale biogas energy system, including a 12 kW gas turbine generator and a chiller, ranges between \$483 and \$1,375/ kW.

The operational and maintenance (O&M) cost is estimated at 5% of the total initial system cost. HOMER input data shown in Table B.16 in appendix B for the system shown in Figure A.30 in appendix A.

#### **2.12.4 Scenario 4 Data**

Scenario 4 combines biogas, PV panels, and batteries to create a cost-effective hybrid energy system that supplies both electricity and heat. Economically, this scenario benefits from reduced fuel costs due to on-site biogas production and improved energy efficiency through waste heat recovery from the generator’s exhaust. The initial investment includes the biogas system (digester, scrubbers, generator), PV panels, battery storage, and heat exchangers. While the upfront capital cost is relatively high, the system significantly lowers operational expenses by reducing dependency on diesel or grid electricity and utilizing recovered heat for poultry air and water heating.

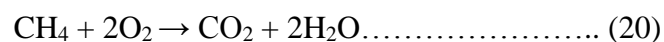
Operation and maintenance (O&M) costs are estimated at approximately 3–5% of the total capital cost annually, mainly covering the biogas system and battery maintenance. Over time, the integrated use of renewable and recovered energy sources improves the return on investment, especially in regions with high fuel or electricity prices.

Detailed economic inputs for this scenario are provided in Table B.17 in Appendix B, and the system configuration is illustrated in Figure A.31 in Appendix A.

### **2.13 Environmental Data**

#### **2.13.1 CO<sub>2</sub> Production**

Biogas is an eco-friendly fuel that helps prevent environmental pollution caused by waste and manure [33]. It has significantly lower CO<sub>2</sub> emissions compared to natural gas, with systems combining biogas and CHP showing CO<sub>2</sub> emissions ranging between 0.02–0.15 tons CO<sub>2</sub> under different conditions [55]. Biogas typically consists of about 25–40% CO<sub>2</sub> [33], making it a direct source of CO<sub>2</sub> emissions. Additionally, the combustion of the methane (CH<sub>4</sub>) present in biogas produces CO<sub>2</sub> as a byproduct, resulting in two distinct sources of CO<sub>2</sub> emissions, as shown in the equation:



For PV system the total CO<sub>2</sub> produced is less due to less CO<sub>2</sub> during operation process [5]. From PV system the 'International Energy Agency's Photovoltaic Power Systems Programme (IEA-PVPS)' [56] mentioned that 36 to 43 g CO<sub>2</sub> per kWh from PV systems.

### **2.13.2 Bio-Fertilizer**

Primarily, the manure from poultry and cow farms is utilized by farmers as fertilizer without undergoing processing. Poultry manure is rich in nitrogen, potassium, and phosphorus, which are vital for soil and plant health. However, a notable issue with using poultry manure as fertilizer is its slow-release time; it takes about 2-3 years to release key components like nitrates. [8] Consequently, this fertilizer should not be applied to the same soil annually to ensure a balance in the amounts of nitrates and other components.

However, the anaerobic digestion process also produces biomass, which can be utilized as a bio-fertilizer [8]. This biomass is highly efficient for use as fertilizer, offering advantages over chemical fertilizers and even organic manure [7].

## **Chapter Three**

### **Results and Discussion**

#### **3.1 Introduction**

This chapter to represent the results from for main criteria, Scenario Performance focusing on the reliability of the systems, economic analysis including (capital cost, LCOE, O&M Cost, Net Present Value (NPV), Payback Period and Energy saving) and environmental evaluation mainly (CO<sub>2</sub> and Bio-fertilizer production) for the four scenarios to meet the demand for a poultry and cow farm. This evaluation will take another approach and meaning by using one of the most important decision criteria which is Multi-Criteria Decision Making.

These results and discussion aim to provide insights into the feasibility and sustainability of the proposed systems and their potential applications in similar contexts.

#### **3.2 Economic analysis results**

Using HOMER economic analysis software. This software enabled modelling of each scenario, including biogas, PV, and battery storage, along with their operating parameters and costs, the results of the four scenarios, including all proposed equipment, provide detailed insights into net present value (NPV), operating and maintenance (O&M) costs, capital costs, payback periods, and energy savings helping to determine the most economically viable solution by balancing the initial investment with long-term benefits.

Mainly, capital cost includes the price for the items and equipment including the price of PV panels, batteries, heat exchangers, absorption chiller, turbines, pumps, etc. and also including the piping for the systems and the installation for the digester.

##### **3.2.1 Scenario 1: Economic Results**

The economic study focuses on a standalone PV system integrated with battery storage to meet the farm's energy demands. Table 3.1 represent summery for the economic parameters analysis.

**Table 3.1***HOMER results for Scenario 1*

Parameter	Value	Unit
System Capital cost	347,603	\$
O&M Cost	15,987.3	\$/year
NPC	566,392	\$
Levelized COE	0.32	\$/kWh
Energy Saving	107,951	\$/year
Payback period	3.22	year

Scenario 1 is cost-effective, with a short 3.22-year payback, good annual savings, and a reasonable LCOE of \$0.32/kWh.

### 3.2.2 Scenario 2: Economic Results

In this scenario, the biogas system is configured to produce electricity through the components illustrated in Figure 2.5. These components typically include a biogas digester for producing the gas, a storage tank, and Combined Heat and Power (CHP) unit that converts the biogas into electrical energy. The HOMER result represented in Table 3.2.

**Table 3.2***HOMER results for Scenario 2*

Parameter	Value	Unit
System Capital cost	281,580	\$
O&M Cost	35,593	\$/year
NPV	616,804	\$
Levelized COE	0.348	\$/kWh
Energy Saving	43,233	\$/year
Payback period	4.2	year

Scenario 2 has a lower capital cost, higher O&M, and slightly higher LCOE (\$0.348/kWh), but offers quick payback in 3 years and solid savings.

### 3.2.3 Scenario 3: Economic Results

In this scenario, both PV and biogas (for thermal and electrical use) are integrated. All components shown in Figure 2.6 are considered in the electrical evaluation. HOMER results are shown in Table 3.3.

**Table 3.3**

*HOMER results for Scenario 3*

Parameter	Value	Unit
System Capital cost	207,248	\$
O&M Cost	6,888	\$/year
NPV	112,978	\$
Levelized COE	0.117	\$/kWh
Energy Saving	86,353	\$/year
Payback period	2.4	year

Scenario 3 offers balanced costs and strong savings, with a 2.4-year payback and LCOE of \$0.117/kWh, making it a solid investment.

### 3.2.4 Scenario 4: Economic Results

In this scenario, biogas is used for both thermal applications and electricity generation, alongside a PV system. The full system, including all is evaluated for both thermal and electrical performance. The simulation results from HOMER are summarized in Table 3.4.

**Table 3.4**

*HOMER results for Scenario 4*

Parameter	Value	Unit
System Capital cost	194,828	\$
O&M Cost	13,486	\$/year
NPC	286,212	\$
Levelized COE	0.161	\$/kWh
Energy Saving	84,708	\$/year
Payback period	2.3	year

The numbers here are very promising. With the lowest LCOE among all scenarios, Scenario 4 clearly stands out in terms of cost efficiency. A payback period of just 2.3

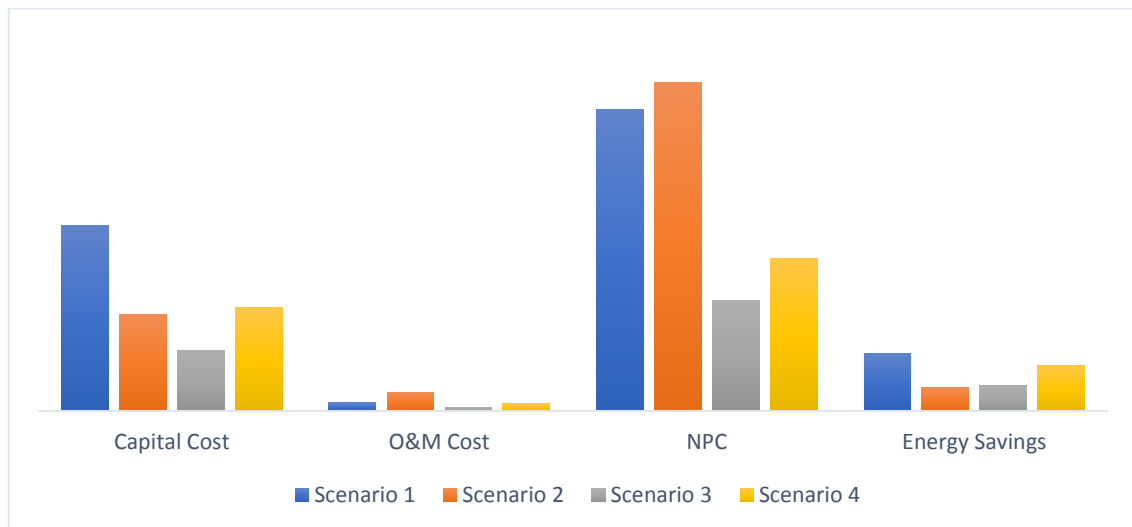
years is especially impressive—it means the system starts saving money quickly. This is largely thanks to the effective use of waste heat from biogas and a well-integrated PV system. Together, they keep both capital and operating costs down, making this a smart financial investment for energy production.

### 3.3 Economic analysis Conclusion

The summary for the HOMER Results represented in Figure 3.1. One of the key economic parameters for comparing scenarios is the Levelized Cost of Energy (LCOE), which helps determine the most cost-effective option for meeting energy needs and evaluating a project's long-term viability. It is a crucial metric for energy *planning*.

**Figure 3.1**

*Economic Performance Results*



As shown in Figure A.32 in Appendix A, Scenario 4 has the lowest LCOE, indicating the most economical energy generation. Scenario 1 has the highest cost of energy, while Scenarios 2 and 3 fall in between with relatively similar values.

This table compares the economic performance of four scenarios based on six key criteria: system capital cost, operation and maintenance cost, net production cost, levelized energy efficiency cost, energy savings, and payback period. Each criterion is ranked using a color-coded system:

- Green (best): indicates the scenario with the best performance for these criteria.
- Blue (best): represents a fairly acceptable result compared to the other scenarios.
- Yellow (poor): shows the lowest performance among the four scenarios.

From the table, Scenario 4 appears to be the most economically effective, achieving the best scores in O&M cost, levelized COE, energy savings, and payback period. Despite not having the lowest capital cost, its balanced performance across key parameters makes it the most favorable option overall.

### **3.4 Environmental analysis results**

The primary environmental evaluation in this research focuses on CO<sub>2</sub> emissions and bio-fertilizer production across the studied scenarios.

#### **3.4.1 CO<sub>2</sub> Production**

The CO<sub>2</sub> production in the four scenarios reflects the diverse impacts of the energy sources and their components, and includes the total GHG emissions generated during the production, transportation, installation and disposal of the system components. In Scenario 1 (PV with batteries), emissions arise from the PV panels and batteries mainly in the production and disposal for the system. In Scenarios 2, 3 and 4 (PV with biogas), CO<sub>2</sub> emissions include the PV system and the combustion of biogas. However, biogas is significantly lower life cycle emissions compared to fossil fuels. This integration of PV and biogas highlights a sustainable approach to reducing the carbon footprint.

The systems' CO<sub>2</sub> production is presented in Table B.18 in appendix B and Figure A.33 in appendix A, calculated using equations (18).

For Biogas Produce 0.446 kg CO<sub>2</sub>/kWh with considering the combustion and the operation emission. And 39.5 g CO<sub>2</sub>/kWh from PV System [5].

In Scenario 1, which includes only PV and battery systems, CO<sub>2</sub> production is relatively low. In contrast, the CO<sub>2</sub> production in Scenarios 2, 3 and 4 is nearly identical.

#### **3.4.2 CO<sub>2</sub> Mitigation**

Mitigation can be assessed by comparing the emissions to those of a diesel generator, which emits approximately 0.75 kg CO<sub>2</sub> per kWh [42]. By using equation (19) the mitigation from the four scenarios can be represented in table B.19 in appendix B and Figure A.34 in appendix A.

CO<sub>2</sub> production and mitigation across the four scenarios reflect the diverse environmental impacts of different energy sources and their integration. In Scenario 1 (PV/Battery), solar and battery use results in the highest CO<sub>2</sub> mitigation, with minimal emissions from PV production and installation. In contrast, Scenarios 2, 3 and 4 (PV/Biogas/Battery) show lower CO<sub>2</sub> mitigation, with biogas contributing to overall emissions, primarily due to its methane content.

### **3.4.3 Bio-Fertilizer**

The Organic waste such as poultry and cow manures can be used as a fertilizer. However, anaerobic digestion provides a highly efficient fertilizer from the digested material. Scenarios 2, 3 and 4 take advantage of this feature, as anaerobic digestion not only contributes to energy production, but also plays a vital role in waste management by converting organic waste into valuable bio-fertilizer. This adds an additional sustainability benefit to the system, reducing the need for chemical fertilizers and helping to close the waste loop by turning it into a resource. In this research the estimated amount of digested organic matter = 832 kg/day.

### **3.5 Multi-Criteria Decision Analysis (MCDA)**

While economic comparison or environmental impact analysis alone may not provide a complete picture, it is important to recognize that some scenarios may offer greater environmental mitigation, while others are more economically feasible. Therefore, relying on just one criterion might lead to suboptimal decision-making. Multi-Criteria Decision Analysis (MCDA) becomes essential in such cases, as it allows for a more comprehensive evaluation by considering both economic feasibility and environmental benefits simultaneously. So, we can define Multi-Criteria Decision Analysis (MCDA) as a valuable method for evaluating and comparing different scenarios, especially when determining the best option is complex due to the involvement of multiple factors which shown in Table B.20 in appendix B.

In this context, MCDA helps in assessing various scenarios by considering several criteria, such as cost, environmental impact, and efficiency. It operates as a weighted scoring model, where each criterion is assigned, a specific weight based on its relative importance. These weights are then applied to the scores each scenario receives for each criterion, allowing for a comprehensive evaluation. By using MCDA, decision-makers

can systematically rank and select the most suitable scenario, balancing the trade-offs between different objectives to make informed, data-driven decisions.

For the weighting criteria, a high emphasis is placed on reliability, as these are off-grid, isolated farms where ensuring a dependable power supply is the top priority. In farms like closed poultry farms, where temperature and ventilation are critical for the well-being of the animals, any disruptions in power could lead to catastrophic outcomes, such as the loss of livestock. Therefore, reliability is paramount to avoid compromising the health of the chickens.

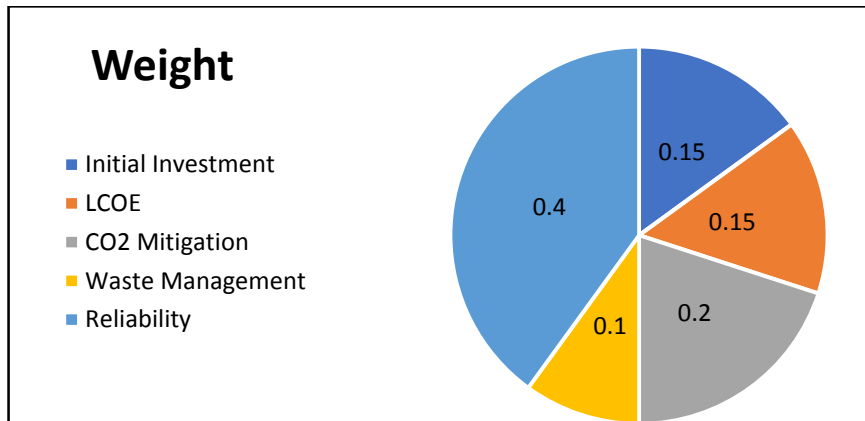
Environmental concerns are a top priority; especially given the challenges these farms face in terms of manure management. Proper waste management not only enhances farm sustainability, but also reduces the environmental impact of waste disposal. Carbon dioxide emissions are also an important measure of how systems impact climate change and how they contribute to reducing GHG's emissions. Therefore, the effectiveness of each scenario in meeting both energy demands and addressing environmental issues is critical to decision-making.

Economically, the investment required to set up the system should be reasonable and justified by the expected benefits. Lower capital costs enhance the project's attractiveness by making it more accessible and reducing financial risk. Additionally, keeping operational costs low is essential for increasing profitability, while a shorter payback period ensures that the investment can be quickly recouped. Overall, the system's cost-effectiveness is highlighted by significant savings in energy consumption and reduced maintenance costs, making it a viable and profitable long-term solution for the farm.

Each criterion gets a weight with total weights equal to 1 as shown in table B.21 in appendix B and Figure 3.2.

**Figure 3.2**

*Evaluation Criteria Weights*



Each criterion for each scenario is assigned a score between 1 and 10 as represented in Table B.22 in appendix B.

The score is depending on the following scoring criteria:

LCOE < 0.2 \$/kWh → score = 8–10

CO<sub>2</sub> mitigation > 90 t/year → score = 9–10

Initial investment > \$330,000 → score = 5 or below

Full waste conversion → score = 8–10

Uses both PV + Biogas + Battery → score = 8-10 (Reliability)

The evaluation of the four scenarios, as shown in Table 3.5, reveals that Scenario 4 scores the highest overall, with a total of 8.15. It performs best in LCOE and matches the highest scores in reliability, CO<sub>2</sub> mitigation, and waste management. Scenarios 2 and 3 follow closely with equal total scores of 8, both showing strong performance in reliability and waste management, though Scenario 2 has the advantage in initial investment. Scenario 1, despite having the highest score in CO<sub>2</sub> mitigation, ranks lowest overall due to lower performance in reliability, waste management, and LCOE.

**Table 3.5***Multi-Criteria Decision Analysis*

Criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Initial Investment	0.75	0.75	0.9	1.05
LCOE	0.9	0.75	1.2	1.2
CO2 Mitigation	1.6	1.2	1.4	1.4
Waste Management	0.6	0.9	0.9	0.9
Reliability	2.4	3.2	3.6	3.6
Total	6.25	6.8	8	8.15

## Chapter Four

### Conclusion and Recommendations

#### 4.1 Conclusion

This study presents a detailed evaluation of an integrated renewable energy system combining biogas, photovoltaic (PV) panels, and battery storage to meet the energy demands of a farm in the Jordan Valley, Palestine. The system's feasibility was assessed across economic, environmental, and reliability criteria over different seasons. The key conclusions are:

##### 1. Economic Evaluation:

Scenario 4 emerges as the most economically viable configuration with the low Levelized Cost of Energy (LCOE) of \$0.161/kWh, the lowest Net Present Cost (NPC) of \$286,212, and a relatively fast payback period of 2.3 years. Although Scenario 1 achieved the highest annual energy savings (\$107,951/year), it suffered from the highest capital cost (\$347,603) and LCOE (\$0.32/kWh). Scenario 2 had moderate performance with a payback period of 4.2 years and the highest NPV (\$616,804), while Scenario 3 followed closely with good energy savings (\$86,353/year) but the highest LCOE (\$0.117/kWh).

##### 2. Environmental Impact:

Scenario 1 achieved the highest CO<sub>2</sub> mitigation (101.1 tCO<sub>2</sub> /year) due to its exclusive use of PV and battery systems, thus producing the lowest CO<sub>2</sub> emissions (5.62 tCO<sub>2</sub> /year). In contrast, Scenarios 2, 3, and 4 rely on biogas combustion, leading to higher CO<sub>2</sub> emissions but also enabling waste-to-energy conversion. Scenario 4 performed well environmentally, with CO<sub>2</sub> mitigation of 59.28 tCO<sub>2</sub> /year, balancing between emissions and sustainability benefits.

##### 3. Multi-Criteria Assessment:

According to the multi-criteria analysis (including LCOE, investment, CO<sub>2</sub> mitigation, reliability, and waste management), Scenario 4 scores the highest overall (7.75 points), making it the most balanced and effective option. Scenarios 2 and 3 both score 7.45 points, showing competitive but slightly lower performance. Scenario 1, despite

excelling in CO<sub>2</sub> mitigation, ranked lowest overall (6.05 points) due to high cost and lower system reliability.

#### **4. Waste Management and Reliability:**

Scenarios 2, 3, and 4 enhance agricultural waste management by using biogas systems effectively. These scenarios also score highly in system reliability (3.2 points), ensuring continuous power supply and reduced dependence on diesel generators.

Integrating renewable sources particularly biogas and PV is a sustainable and economically sound strategy for off-grid farms. Scenario 4, with its superior balance of cost, environmental performance, and reliability, is identified as the optimal solution. This study serves as a practical framework for the design and implementation of hybrid renewable energy systems that align with energy transition goals and environmental sustainability.

#### **4.2 Recommendations**

According to this research many recommendations can be suggested as follow:

1. Encourage further research and practical studies to improve the design, efficiency and implementation of biogas systems suitable for local conditions in Palestine, especially in rural and remote areas.
2. Encourage and advocate for funding and support from the Palestinian National Authority for biogas plants, especially for farmers and rural communities. This support can enhance cooperation between the energy, environment and agriculture sectors to implement sustainable energy solutions.
3. Recommendation to establish biogas production plants in the main landfill sites in Palestine.
4. Integrating biogas production into the waste management strategy in Palestine. This includes implementing large-scale food waste collection programs and establishing additional anaerobic digestion plants throughout the West Bank.
5. Providing training programs for farmers, technicians and stakeholders to enhance the knowledge and skills required to operate and maintain biogas plants and integrate them with other renewable energy systems such as the well-known solar PV system.

6. Enhancing cooperation between the public sector, private sector investors and international organizations to finance and scale up renewable energy initiatives, including PV and biogas systems.
7. Conduct awareness campaigns that highlight the economic, environmental and security benefits of energy generated from renewable energy systems to encourage their adoption among farmers and local communities.

## List of Abbreviations

Abbreviation	Meaning
AD	Autonomy days
Ah	Ampere hour
Avg.	Average
CCHP	Combined Cooling, Heat and Power
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbon dioxide
COE	Cost of Energy
COP	Coefficient of Performance
D. F	Daily Feed
DoA	Days of Autonomy
DoD	Depth of Discharge
E	Energy
EF	Emission Factor
f	Frequency
GHG	Green House Gases
h	Height
H <sub>2</sub> S	Hydrogen sulfide
H <sub>2</sub> S	hydrogen sulfide
HOMER	Hybrid Optimization of Multiple Energy Resources
IEA	International Energy Agency
IEA-PVPS	'International Energy Agency's Photovoltaic Power Systems Programme
IRR	Internal rate of return
kg	Kilo gram
kW	Kilo Watt
kWh	Kilo Watt hour
LCOE	Levelized cost of Energy
LiBr	Lithium bromide
m	Meter
MCDA	Multi-Criteria Decision Analysis
MJ	Mega Joule
NH <sub>3</sub>	Ammonia

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NPV	Net Present Value
O&M	Operating and Maintenance Cost
O <sub>2</sub>	Oxygen
P	Power
p	Poles
pH	potential of hydrogen
PP	Payback period
PSR	Peak Solar Radiation
PV	Photovoltaic
r	Radius
R. T	Retention Time
s	Second
SC	System Cost
SF	Safety Factor
T	Time
tCO <sub>2</sub>	Ton CO <sub>2</sub>
TS	Total Solids
V	Voltage
VS	Volatile Solids

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# Appendices

## Appendix A

### Figures

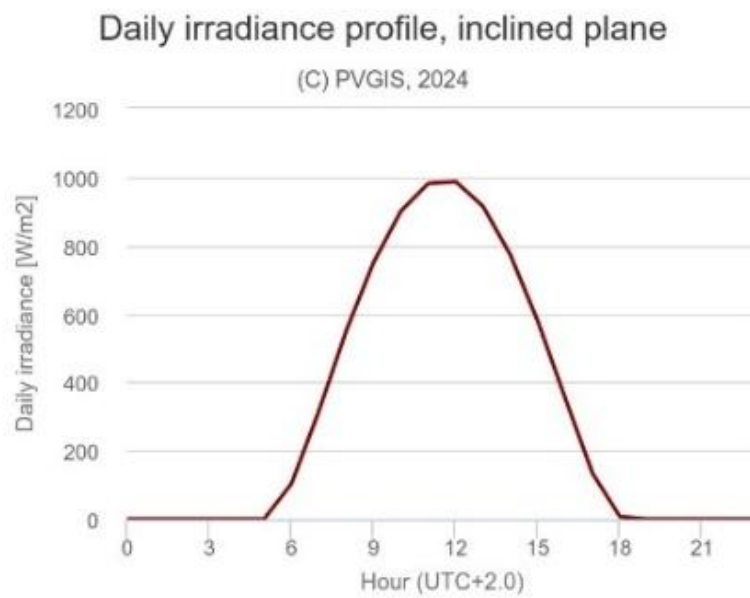
**Figure A. 1**

*Geographical location of the site (source: Google earth)*



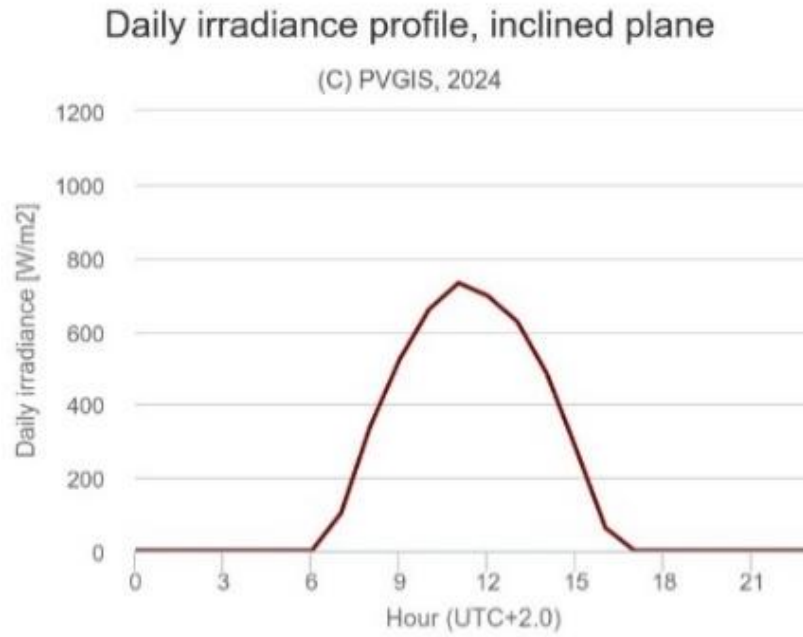
**Figure A. 2**

*Period 1 peak sun days for study area (Source: PVGIS)*



**Figure A. 3**

*Period 2 peak sun days for study area (Source: PVGIS)*



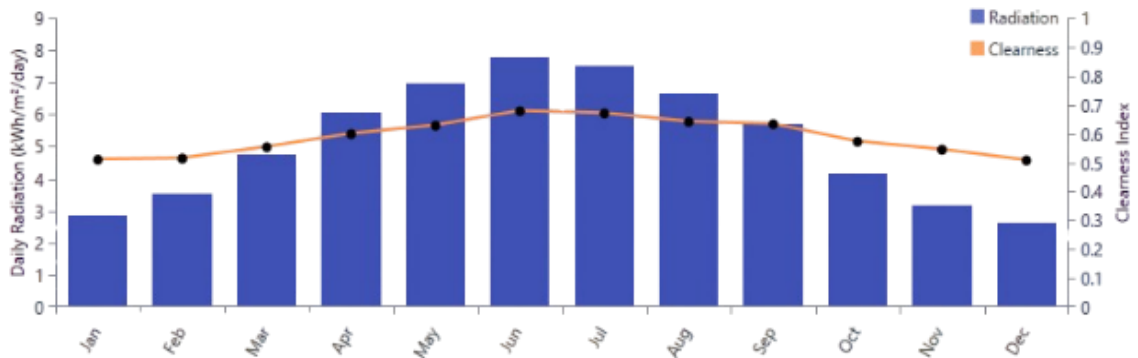
**Figure A. 4**

*Site Monthly peak temperature*



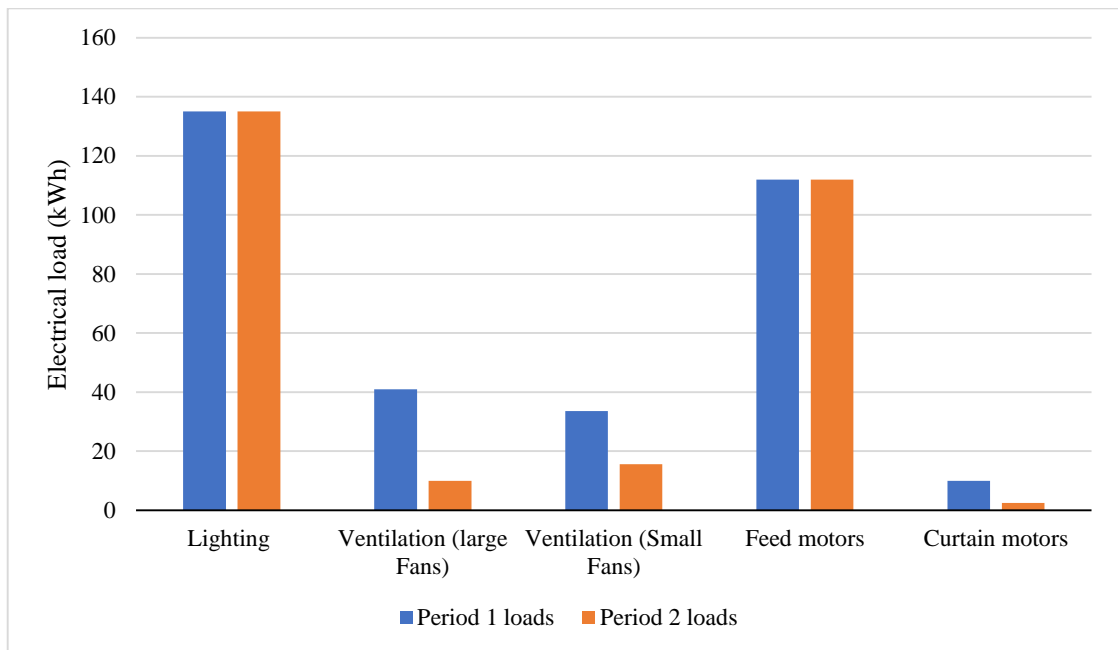
**Figure A. 5**

*Daily Solar Radiation*



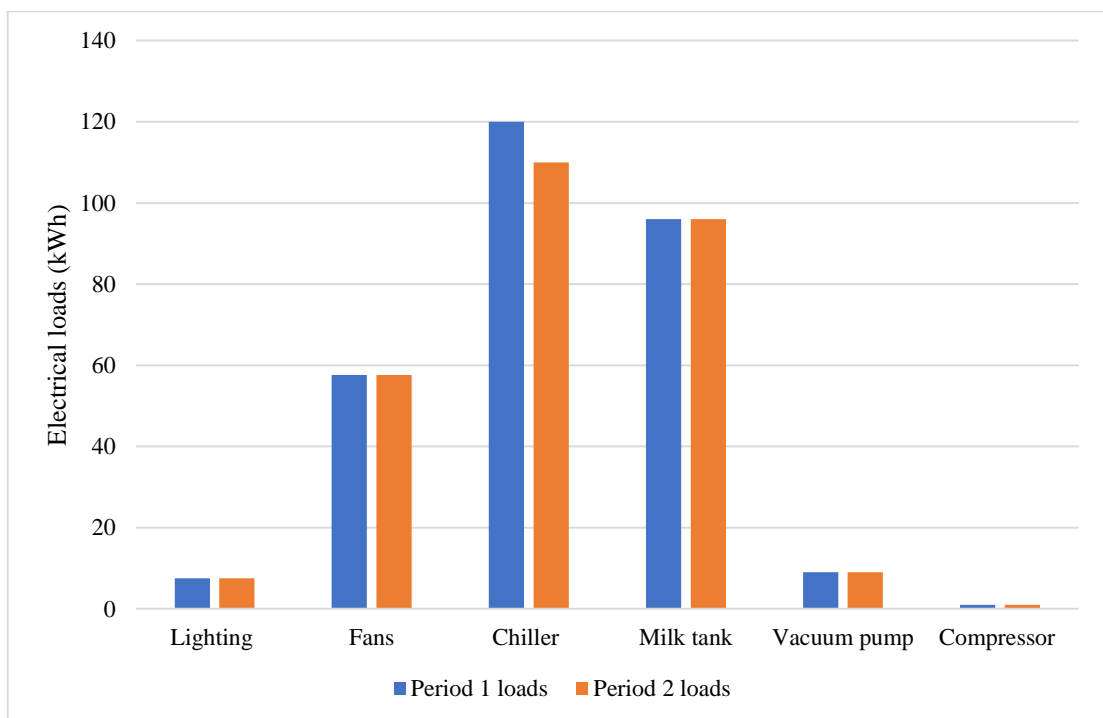
**Figure A. 6**

*Periods loads for broiler farm*



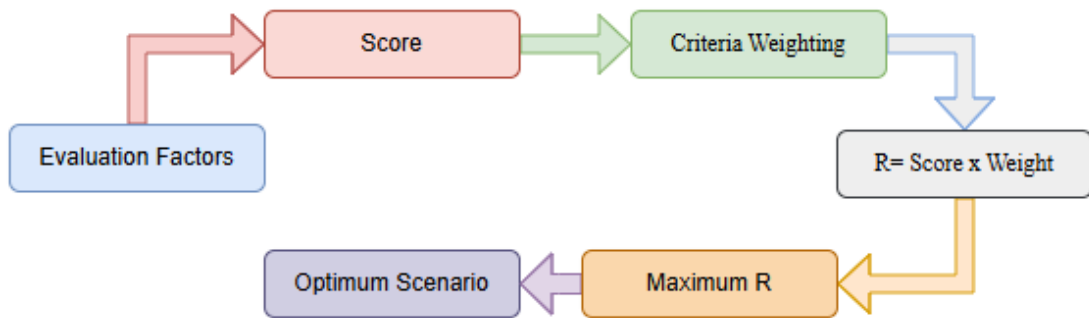
**Figure A. 7**

*Periods loads for Cow farm*



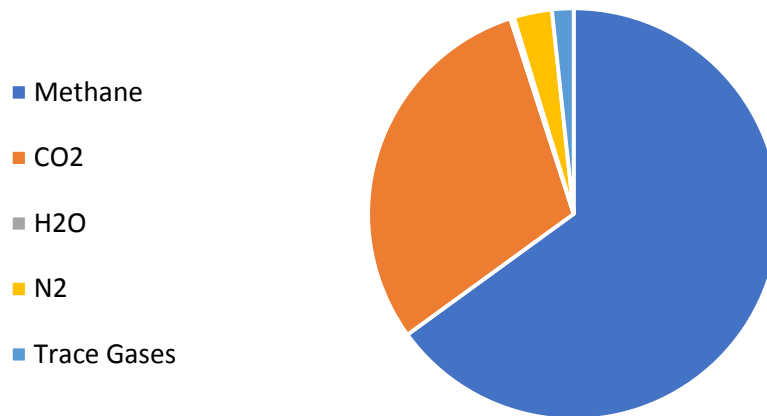
**Figure A. 8**

*Multi-Criteria Decision Analysis Structure*



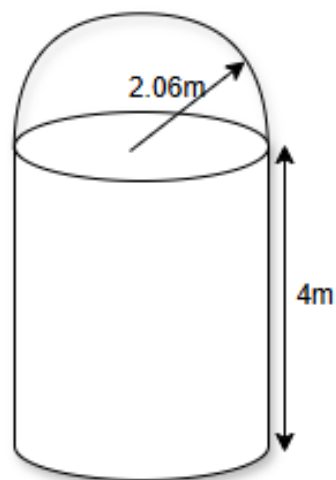
**Figure A. 9**

*Biogas Composition*



**Figure A. 10**

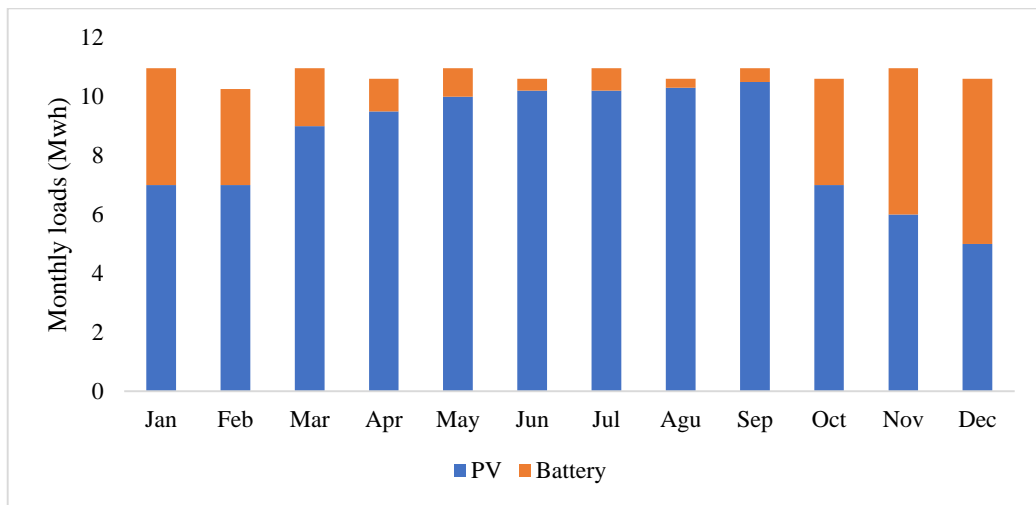
*Digester dimensions*





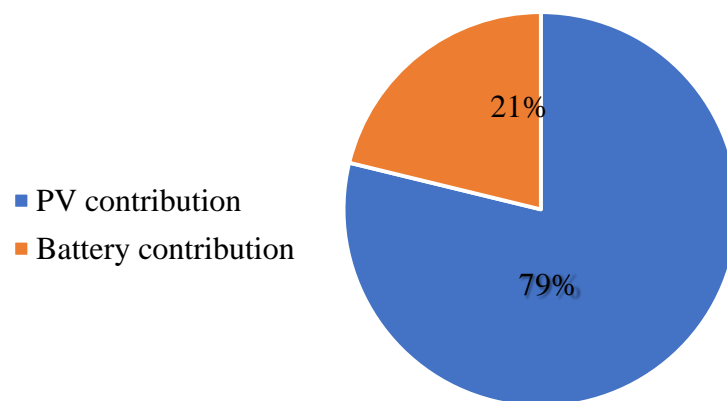
**Figure A. 14**

*Scenario 1 Monthly sources energy contribution*



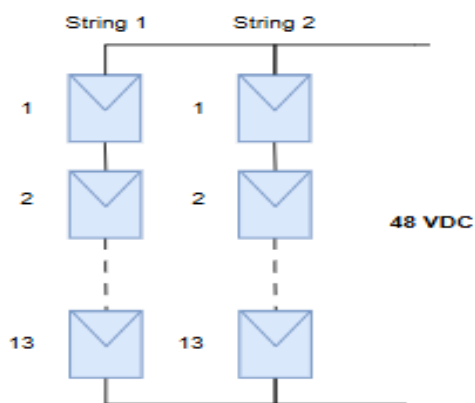
**Figure A. 15**

*Scenario 1 Annual Contribution PV/Battery*



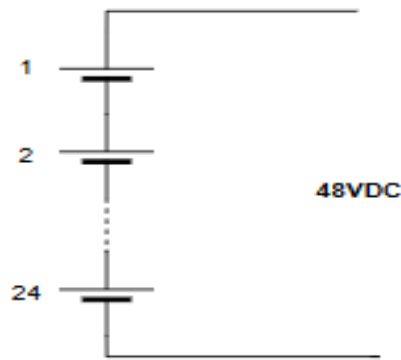
**Figure A. 16**

*Scenario 2 and 4 PV Configuration/ inverter*



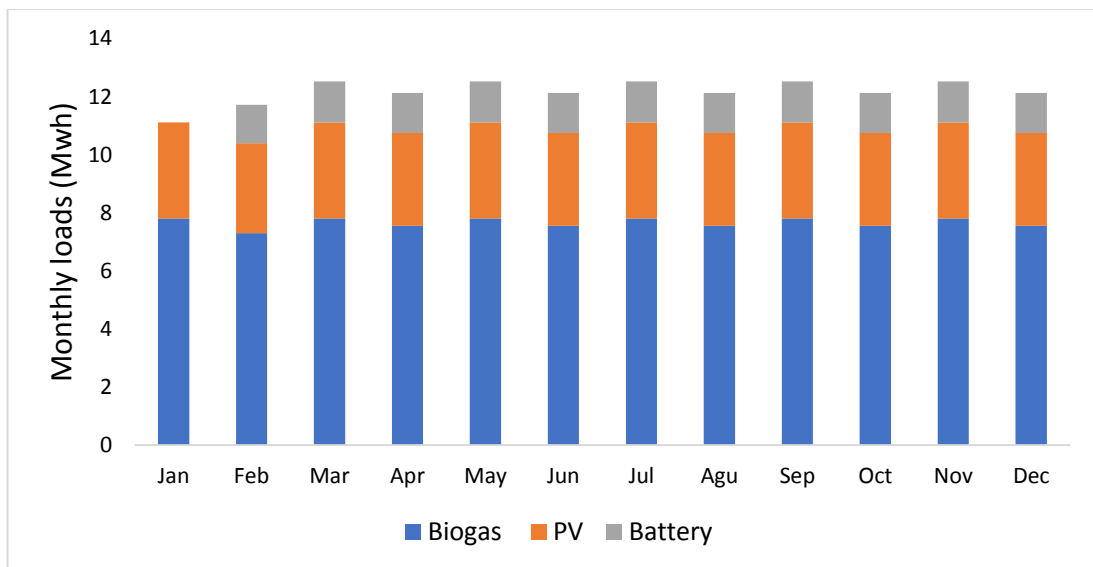
**Figure A. 17**

*Scenario 2 and 4 Storage Battery Configuration*



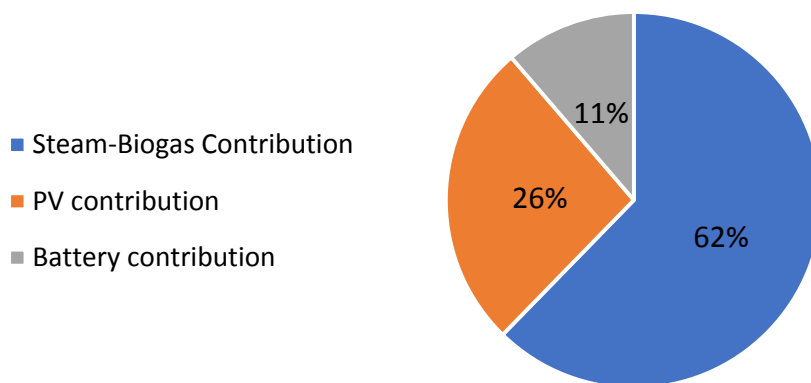
**Figure A. 18**

*Scenario 2 Monthly sources energy contribution*



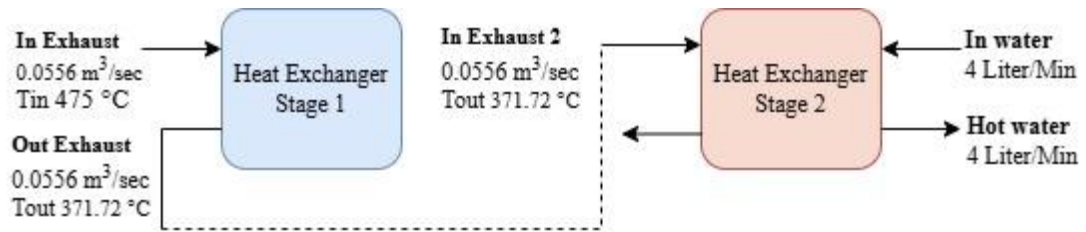
**Figure A.19**

*Scenario 2 Annual Contribution Steam-Biogas/PV/Battery*



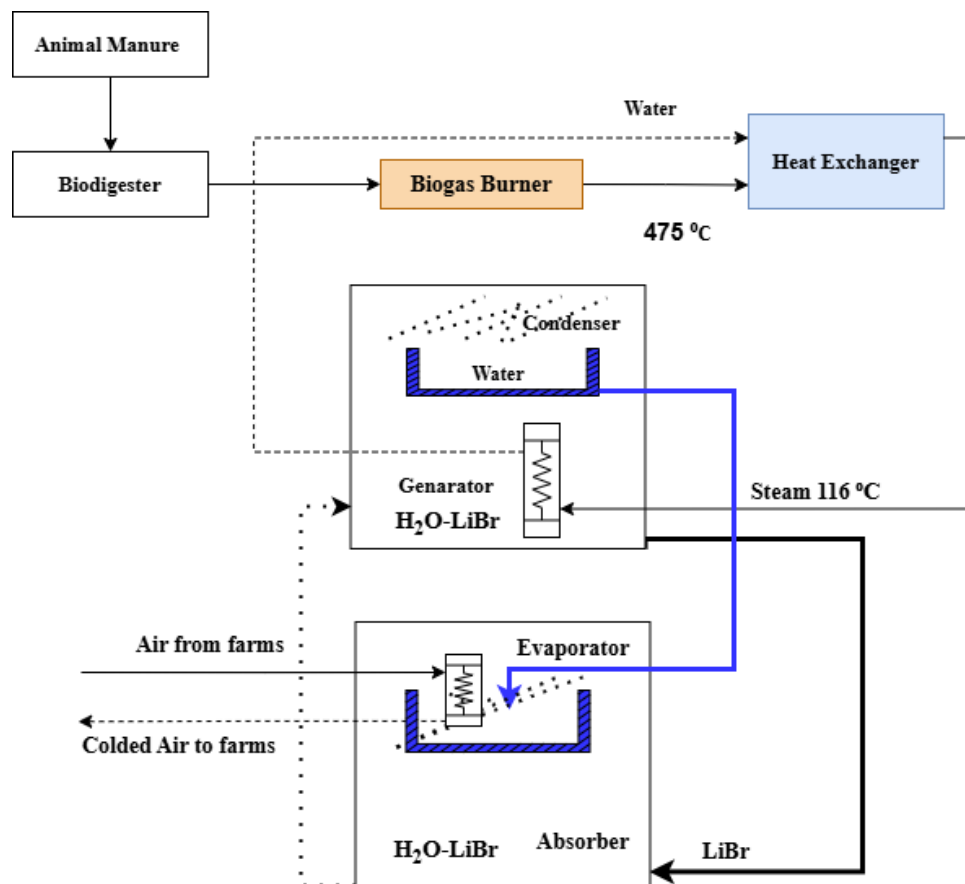
**Figure A. 20**

*Schematic of two stage heat exchanger*



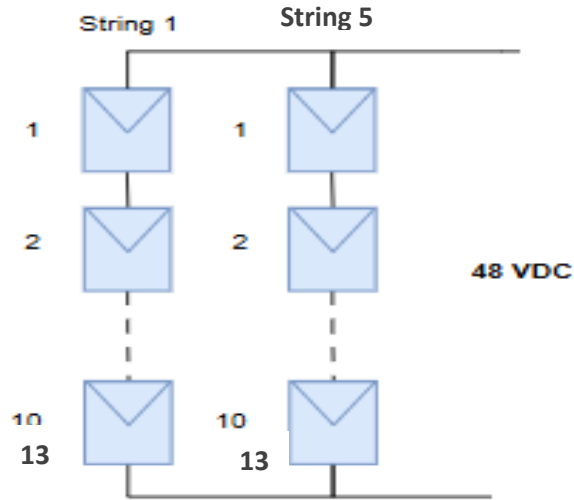
**Figure A. 21**

*Schematic of Absorption chiller*



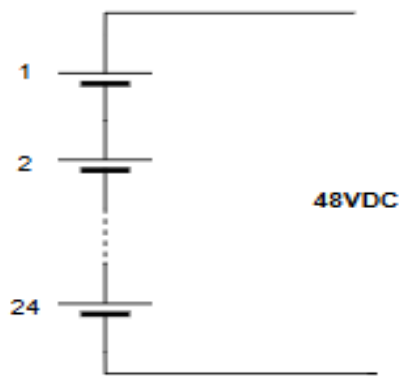
**Figure A. 22**

*Scenario 3 PV Configuration/ inverter*



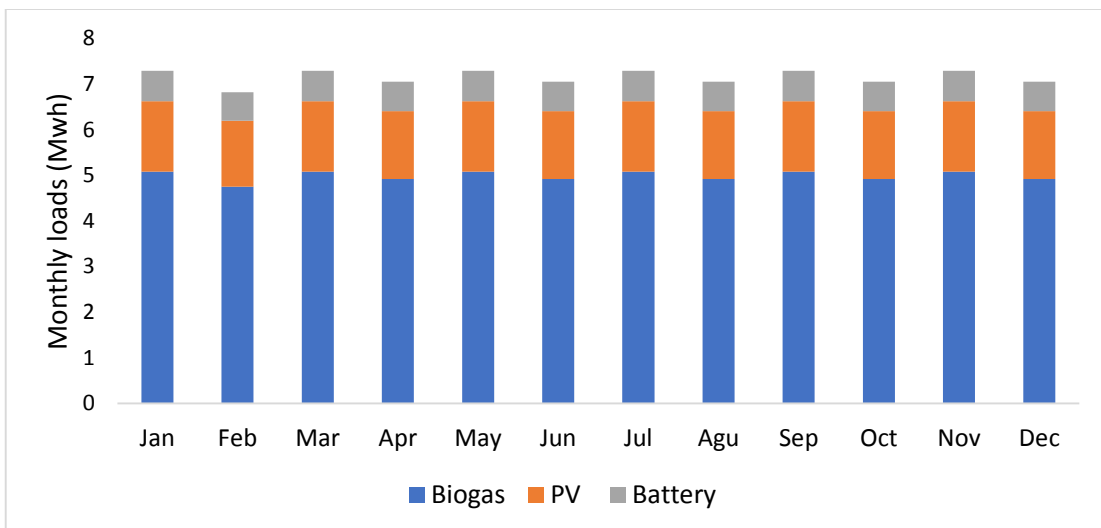
**Figure A. 23**

*Scenario 3 Storage Battery Configuration*



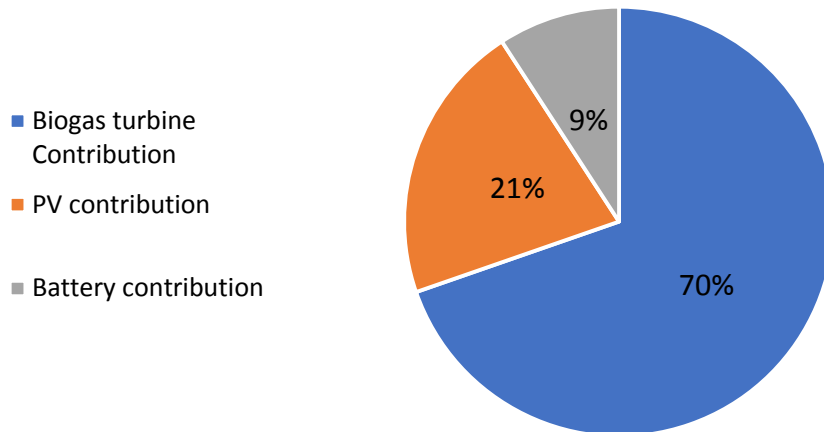
**Figure A. 24**

*Monthly Energy Contribution from Each Source in Improved Scenario 3*



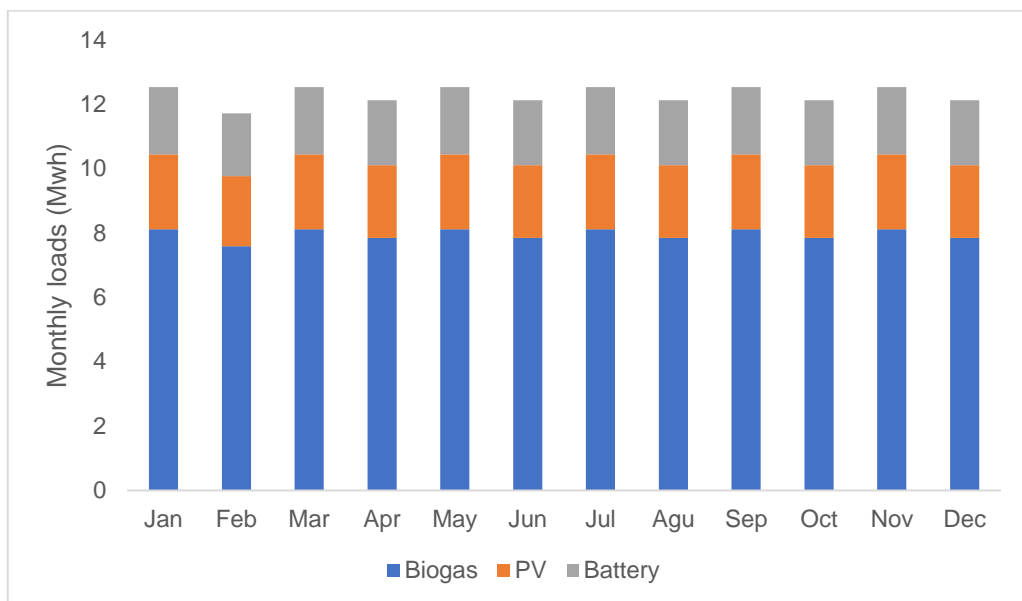
**Figure A. 25**

*Scenario 3 Annual Contribution Steam-Biogas/PV/Battery*



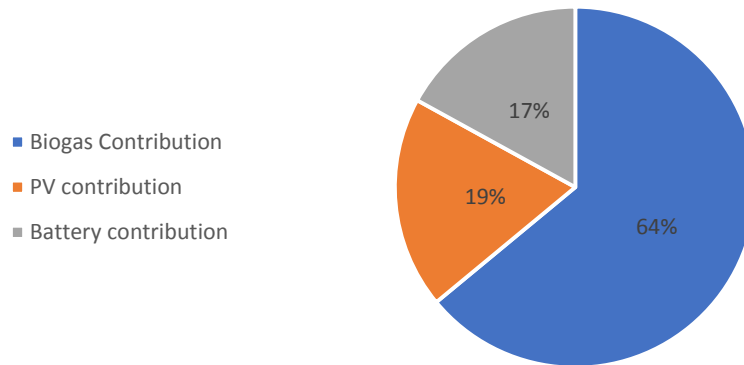
**Figure A. 26**

*Monthly Energy Contribution from Each Source in Improved Scenario 4*



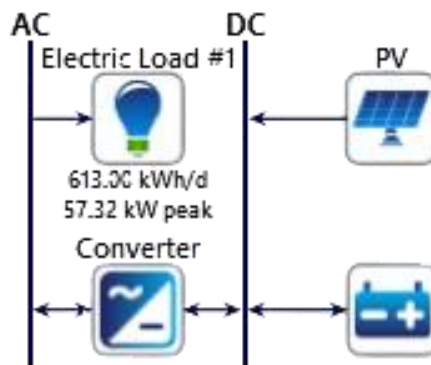
**Figure A. 27**

*Scenario 4 Annual Contribution Biogas/PV/Battery*



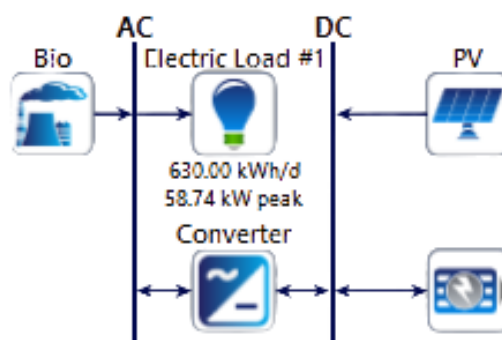
**Figure A. 28**

*HOMER Schematic of Scenario 1*



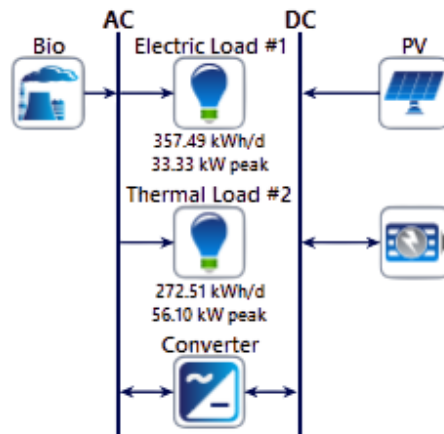
**Figure A. 29**

*HOMER Schematic of Scenario 2*



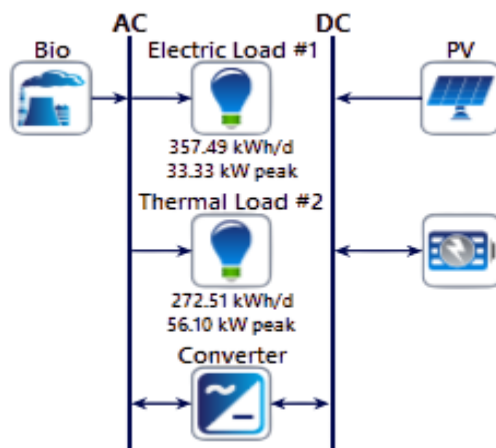
**Figure A. 30**

*HOMER Schematic of Scenario 3*



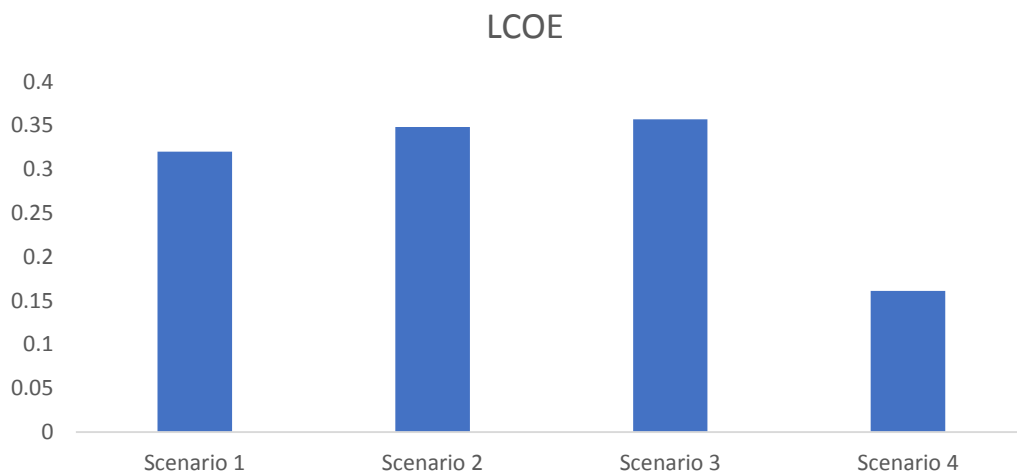
**Figure A. 31**

*HOMER Schematic of Scenario 4*



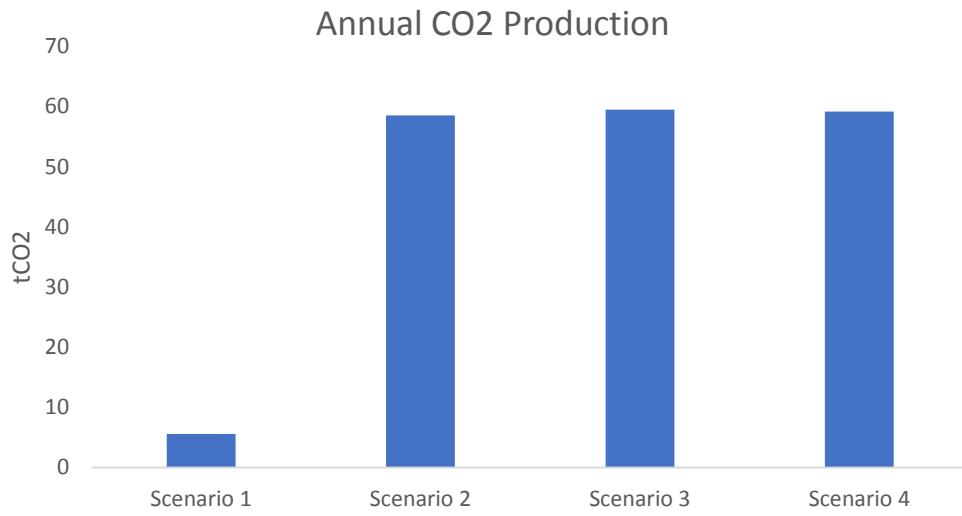
**Figure A. 32**

*LCOE for Scenarios*



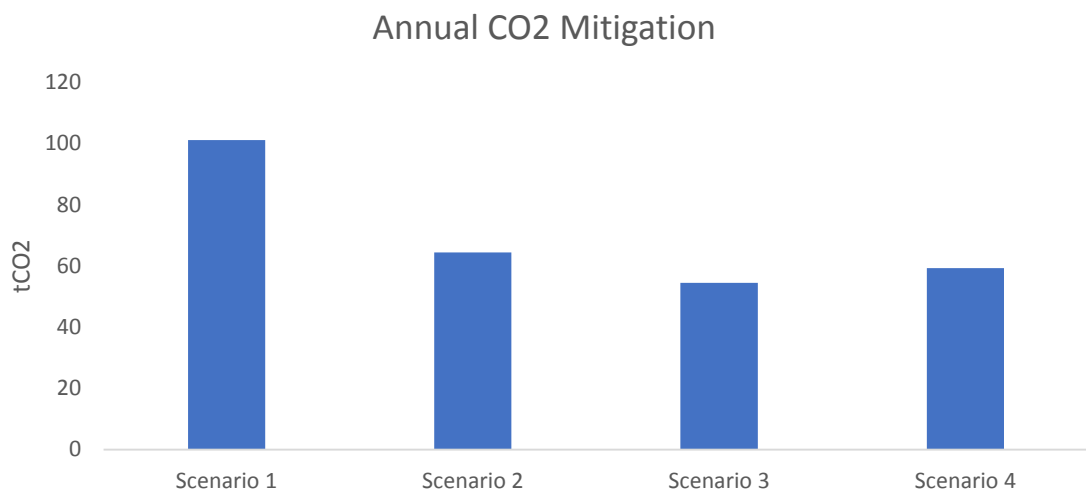
**Figure A. 33**

*Annual CO2 Production*



**Figure A. 34**

*Annual CO2 Mitigation*



## Appendix B

### Tables

**Table B. 1**

*Estimated waste produced*

Avg. Weight/Cow	480 kg
Avg. Weight/Poultry	1.3 kg
Production/Cow	12.6 kg/cow
Production/Poultry	0.041 kg/poultry

**Table B. 2**

*Farm size and Manure production summary.*

Cow Farm size	50 heads
Poultry Farm size	10,000 heads
Daily Cow Manure	0.6345 tons/day
Daily Poultry Manure	0.41 tons/day
Production/Cow	12.6 kg/cow
Production/Poultry	0.041 kg/poultry
Collection Cycle	35 days
Total Cow Manure	22.2 tons/cycle
Total Poultry Manure	14.35 tons/cycle

**Table B. 3**

*Characteristics of cow and poultry manures.*

	Cow manure	Poultry manure
Total Solids (TS%)	24.56%	28.25%
Volatile solids (VS% of TS)	75.3%	72.35%
pH	7.6	8.3
Nitrogen (%)	1.56%	3.51%
C/N	10.2	11.42

**Table B. 4**

*Daily Manure Composition for Cow Farm.*

Total manure	Total solids	Total Volatile of TS	Nitrogen
630 kg	154.7 kg	116.489 kg	9.828 kg

**Table B. 5***Daily Manure Composition for Poultry Farm*

Total manure	Total solids	Total Volatile of TS	Nitrogen
315 kg	89.08 kg	64.45 kg	14.39 kg

**Table B. 6***Estimated amount biogas produced (m<sup>3</sup>/kg VS)*

	TS	VS of TS	Biogas m <sup>3</sup> /kg VS	Average
Poultry manure	28.25%	72.35%	0.3-0.8	0.55
Cow manure	24.56%	75.3%	0.6-0.8	0.7

**Table B. 7***Biogas main characteristics [33,34]*

Parameter	Value
Methane Content	50-75 %
Carbon Dioxide Content	25-40 %
Nitrogen Content	1-3 %
Water vapor Content	0.3 %
Calorific Value	20-26 MJ/m <sup>3</sup>

**Table B. 8***The concentration of TS and VS in the mixing manures ratio 2:1*

Total manure	Total solids	Total Volatile of TS	Nitrogen
945 kg	243.78 kg	180.94 kg	24.22 kg
	26.012 %	74.036 %	3.71 %

**Table B. 9***Scenario 2 main parameters of the heat exchanger*

Heat load	6.92 kW
C <sub>p</sub> exhaust	1.005 kJ/kg. °C [55]
Volume flow rate	0.0556 m <sup>3</sup> /sec [5]
Inlet exhaust T <sub>in</sub>	475 °C
Outlet exhaust T <sub>out</sub>	371.72 °C
C <sub>p</sub> Air	1.005 kJ/kg. °C
Volume flow rate	0.573 m <sup>3</sup> /sec
ΔT air	10 °C

**Table B. 10***Scenario 2 PV System parameters and Battery Storage.*

Period 1 PV energy contribution	175.4 kWh
Period 2 PV energy contribution	50.14 kWh
Avg. PV energy contribution	103.54 kWh
Avg. Peak Sun Hours	5.2 hours
PV peak power	20 kW
Battery size	2800 Ah
Number of batteries	24 Batteries

**Table B. 11***Scenario 3 Heat exchanger parameters-stage 1*

Farm Heating load	6.92 kW
$C_p$ exhaust	1.005 kJ/kg. °C [46]
Volume flow rate	0.0556 m <sup>3</sup> /sec [47]
Inlet exhaust $T_{in}$	475 °C
Outlet exhaust $T_{out}$	371.72 °C
$C_p$ Air	1.005 kJ/kg. °C
Air volume flow rate	0.573 m <sup>3</sup> /sec
$\Delta T$ Air	10 °C

**Table B. 12***Scenario 3 heat exchanger parameters-stage 2*

$C_p$ exhaust	1.005 kJ/kg. °C [46]
Exhaust Volume flow rate	0.0556 m <sup>3</sup> /sec [5]
Inlet exhaust $T_{in}$	371.72 °C
Outlet exhaust $T_{out}$	267.54 °C
$C_p$ water	4.186 kJ/kg. °C
Water Volume flow rate	4 Liter/Min [46]
$\Delta T$ water	25 °C [46]

**Table B. 13***Scenario 3 Absorption chiller parameters*

Cooling load	268.2 MJ
COP	0.72
Energy needed	383.14 MJ
Power needed	8.87 kW
Steam Inlet Temperature	116 °C
Steam mass flow rate	11.8 kg/h
Condenser cooling water in	20
Condenser cooling water out	40
Evaporation Temperature	5 °C
Environment Temperature	26 °C
Farm needed Temperature	20 °C
$\dot{m}_{\text{cooled\_air}}$	12.35 kg/s

**Table B. 14***HOMER Scenario 1 required data*

Parameter	Value	Unit
PV power	75	kW
PV Lifetime	20	Year
PV capital cost	900	\$/kW
Converter Cost	300	\$
PV O&M	20	\$/kW/year
Battery capacity	2100	Ah/Battery
Number of strings	2	String
Number of batteries	60	Battery/String
Battery Capital Cost	800	\$/Battery

**Table B. 15***HOMER Scenario 2 required data*

Parameter	Value	Unit
PV power	20	kW
PV Lifetime	20	Year
PV capital cost	900	\$/kW
PV O&M	20	\$/kW/year
Converter Cost	300	\$
Battery capacity	2,800	Ah/Battery
Number of strings	1	String
Number of batteries	24	Battery/String
Battery Capital Cost	800	\$/Battery
Biogas digester Cost including installation	58,360	\$
Steam-CHP Cost	21,830	\$
Heat exchanger Cost	2,000	\$
Biogas system O&M	0.93	\$/Operating Hour

**Table B. 16***HOMER Scenario 3 required data*

Parameter	Value	Unit
PV power	16	kW
PV Lifetime	20	Year
PV capital cost	900	\$/kW
PV O&M	20	\$/kW/year
Converter Cost	250	\$
Battery capacity	450	Ah/Battery
Number of strings	1	String
Number of batteries	24	Battery/String
Battery Capital Cost	650	\$/Battery
Biogas digester Cost	58,360	\$
Gas Turbine-Generator Cost	930	\$/kW
Heat exchanger Cost	2,000	\$
Biogas system O&M	0.93	\$/Operating Hour

**Table B. 17***HOMER Scenario 4 required data*

Parameter	Value	Unit
PV power	20	kW
PV Lifetime	20	Year
PV capital cost	900	\$/kW
PV O&M	20	\$/kW/year
Converter Cost	300	\$
Battery capacity	2,800	Ah/Battery
Number of strings	1	String
Number of batteries	24	Battery/String
Battery Capital Cost	800	\$/Battery
Biogas digester Cost including installation	46,500	\$
Heat exchanger Cost	2,000	\$
Biogas system O&M	0.93	\$/Operating Hour

**Table B. 18***Annual CO2 Production*

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual PV CO <sub>2</sub> Production	5.62 tCO <sub>2</sub>	1.5 tCO <sub>2</sub>	1.2 tCO <sub>2</sub>	1.5 tCO <sub>2</sub>
Annual Biogas CO <sub>2</sub> Production	-	57.04 tCO <sub>2</sub>	57.99 tCO <sub>2</sub>	57.65 tCO <sub>2</sub>
Total Production	5.62 tCO <sub>2</sub>	58.54 tCO <sub>2</sub>	59.49 tCO <sub>2</sub>	59.15 tCO <sub>2</sub>

**Table B. 19***Annual CO2 Mitigation*

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual CO <sub>2</sub> Mitigation	101.1tCO <sub>2</sub>	64.39 tCO <sub>2</sub>	54.43 tCO <sub>2</sub>	59.28 tCO <sub>2</sub>

**Table B. 20***Comparison of Economic Parameters Across Scenarios*

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4
System Capital cost	Best	Better	Bad	Better
O&M Cost	Better	Bad	Bad	Better
NPC	Better	Bad	Better	Bad
Levelized COE	Bad	Bad	Bad	Better
Energy Saving	Better	Bad	Bad	Bad
Payback period	Bad	Bad	Bad	Better

■ Best   
■ Better   
■ Bad

**Table B. 21***Evaluation Criteria Weights*

Criteria	Weight
Initial Investment	0.15
LCOE	0.15
CO2 Mitigation	0.2
Waste Management	0.1
Reliability	0.4
Total	1

**Table B. 22***Evaluation Scenarios Scores*

Criteria	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Initial Investment	5	5	6	70...0...
LCOE	6	5	8	8
CO2 Mitigation	8	6	7	7
Waste Management	6	9	9	9
Reliability	6	8	9	9



جامعة النجاح الوطنية  
كلية الدراسات العليا

## أنظمة الطاقة الكهروضوئية والغاز الحيوي المتكامل لتربية الدواجن: تحسين إنتاج الكهرباء والحرارة

إعداد

تسنيم ناصر يوسف يعقوب

إشراف

د. معين عمر

قدمت هذه الرسالة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس - فلسطين.

## أنظمة الطاقة الكهروضوئية والغاز الحيوي المتكامل لتربية الدواجن: تحسين إنتاج الكهرباء والحرارة

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### الملخص

استجابةً للطلب المتزايد على أنظمة الطاقة المستدامة واللامركزية في المناطق الزراعية، تبحث هذه الدراسة في جدوى نظام طاقة متجدد هجين يجمع بين الغاز الحيوي والطاقة الشمسية الكهروضوئية (PV) وتخزين البطاريات لتلبية احتياجات الطاقة لمزرعة في منطقة الأغوار - فلسطين. تم تقييم أربع تشكيلات مختلفة للنظام من حيث الأداء الفني، والجدوى الاقتصادية، والأثر البيئي.

من بين الخيارات التي تم تقييمها، أظهر السيناريو الرابع الأداء الأكثر توازناً، حيث حقق أقل تكلفة مستوية للطاقة (LCOE) بمقدار 0.161 دولار/كيلوواط ساعة، وتكلفة حالية صافية (NPC) بلغت 286,212 دولاراً، وتوفيراً سنوياً في الطاقة بلغ 84,708 دولارات، وفترة استرداد لا تتجاوز 2.3 سنة. كما ساهم في تقليل انبعاثات ثاني أكسيد الكربون بمقدار 59.28 طناً من CO<sub>2</sub> سنوياً، ودمج استخدام الغاز الحيوي بشكل فعال، مما عزز من إدارة النفايات وإنتاج الطاقة النظيفة.

في المقابل، أظهرت السيناريوهات 1 و2 و3 تبايناً في التكاليف والمزايا. حيث حقق السيناريو الأول أعلى معدل لتقليل انبعاثات CO<sub>2</sub> (بمقدار 101.1 طن CO<sub>2</sub>/سنة) لاعتماده الكامل على الطاقة الشمسية وتخزين البطاريات، إلا أنه كان الأعلى من حيث تكلفة الطاقة (0.32 دولار/كيلوواط ساعة) وتكلفة الاستثمار (347,603 دولارات)، مما يجعله الأقل جدوى اقتصادياً. أما السيناريو الثاني والثالث فقد استخدموا الغاز الحيوي بشكل أكثر فعالية ووفرا مزايا أفضل في إدارة النفايات، لكن وعلى الرغم من ارتفاع الانبعاثات، كانت مؤشرتهما الاقتصادية أقل كفاءة مقارنة بالسيناريو الرابع، حيث بلغت تكلفة الطاقة في السيناريو الثاني 0.348 دولار/كيلوواط ساعة، وفي السيناريو الثالث 0.117 دولار/كيلوواط ساعة، مع فترات استرداد قدرها 4.2 و2.4 سنة على التوالي.

واستناداً إلى تحليل متعدد المعايير (MCDA) شمل عوامل مثل الاستثمار الرأسمالي، وتكلفة الطاقة، والأثر البيئي، والموثوقية، وتحويل النفايات، حصل السيناريو الرابع على أعلى تقييم إجمالي، مما يؤكد تفوقه في تقديم طاقة مستدامة وفعالة من حيث التكلفة للمزارع في المناطق النائية.

وتؤكد هذه الدراسة أن أنظمة الطاقة المتجددة المتكاملة، وخاصة تلك التي تجمع بين الطاقة الشمسية والغاز الحيوي، تمثل حلاً عملياً وقابلاً للتوسع لتلبية احتياجات الطاقة خارج نطاق الشبكة. كما تعزز الاستقلالية في الطاقة، وتقلل من الاعتماد على الوقود الأحفوري، وتحسن الاستدامة البيئية في السياقات الزراعية الريفية.

**الكلمات المفتاحية:** الطاقة المتجددة الهجينة؛ الغاز الحيوي؛ الخلايا الكهروضوئية (PV)؛ تخزين البطاريات؛ مزارع الدواجن؛ تحسين استهلاك الطاقة؛ أنظمة خارج الشبكة؛ فلسطين؛ الاستدامة؛ تحويل النفايات إلى طاقة.