TECHNO-ECONOMIC ANALYSIS OF PV-DIESEL-BATTERY HYBRID SYSTEMS FOR POULTRY FARMS IN NORTH CAROLINA

by

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ABSTRACT

DAVID SIMONSON. Techno-Economic Analysis of PV-Diesel-Battery Hybrid Systems for Poultry Farms in North Carolina. (Under the direction of DR. WEIMIN WANG)

The increasing demand for chicken and egg production in the US has led to more poultry farms being built as the industry grows. North Carolina is the 4th largest state for poultry production and the poultry industry contributes more than 40% of North Carolina's total farm income. For many poultry growers, energy cost is their second highest expense, right behind the house mortgages. Cutting utility bills via renewable energy generation on site is important to increase the profitability of poultry growers. This study intends to perform a techno-economic analysis of using PV-diesel-battery hybrid systems in poultry farms.

The techno-economic analysis is conducted via the use of HOMER simulation software. HOMER utilizes user inputs for various system components to simulate, optimize, and conduct sensitivity analysis to find the most economical solutions. In this work, the electric load profile is based on the actual metered power with 15-minute intervals for a poultry farm in NC. Typical meteorological year data are used for solar radiation and ambient air temperature. A generic configuration is defined separately for grid-connected systems and off-grid systems. Major component sizes are then optimized using HOMER for different cases that vary with the utility rate structure (e.g., block rates and time-of-use rates) and solar power compensation mechanisms (i.e., net metering, net billing, and buy-all and sell-all).

For grid-connected systems, the results show that battery is excluded in the optimal system configuration, which indicated the use of battery is not cost-effective in grid-connected systems at present because of the high battery cost. The utility rate and solar power compensation mechanism

play determinant roles on the profitability of PV investment. For the case of EnergyUnited (an electric cooperative in North Carolina) which offers a low rate at ~4.7 ¢/kWh and the net metering option, the smallest PV size is always selected and the net present cost (NPC) is higher than the current farm operation without the use of PV, which indicates that PV investment is not profitable. However, for the case of REMC (another electric cooperative) which offers a high rate at ~8.05 ¢/kWh, PV investment is profitable if net metering is the compensation mechanism and the block rate structure is used.

For the off-grid PV-diesel-battery hybrid system, the optimal system configuration consists of a 250-kW PV array, a 394-kWh battery system, and a 161-kW converter along with the 100-kW diesel generator, which yielded an NPC of $782722, and the off-grid hybrid system has a much higher NPC ($370,000 to $560,000) than the grid-connected systems. The results of sensitivity analysis show that for grid-connected systems the power purchase price is the variable that has the largest impact on system NPC. However, for the case of REMC rate structure, reducing the PV price by 25% can make PV investment profitable even if net billing is used as the compensation mechanism. For the off-grid hybrid system, the system NPC is most sensitive to diesel fuel price, followed by the PV price and the battery price.

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LIST OF ABBREVIATIONS

AC: ANNUALIZED COST

BASA: BUY-ALL-SELL-ALL

BOS: BALANCE OF SYSTEM

BR: BLOCK RATE

CC: CYCLE CHARGING

CO-OP: COOPERATIVE

DOE: THE DEPARTMENT OF ENERGY

EPC: ENGINEERING, PROCUREMENT, AND CONSTRUCTION

GHI: GLOBAL HORIZONTAL IRRADIANCE

IOU: INVESTOR-OWNED UTILITIES

LCOE: LEVELIZED COST OF ELECTRICITY

LF: LOAD FOLLOWING

MGS: MEDIUM GENERAL SERVICE

MUNIS: MUNICIPALS

NB: NET BILLING

NM: NET METERING

NOCT: NOMINAL OPERATING CELL TEMPERATURE

NPC: NET PRESENT COST

NSRDB: NATIONAL SOLAR RADIATION DATABASE

O&M: OPERATION AND MAINTENANCE

OE: OFFICE OF ELECTRICITY DELIVERY AND ENERGY RELIABILITY

PS: PREDICTIVE DISPATCH STRATEGY

PV: SOLAR PHOTOVOLTAICS

REAP: RURAL ENERGY FOR AMERICA PROGRAM

REMC: RANDOLPH ELECTRIC MEMBERSHIP CORPORATION

TMY: TYPICAL METEOROLOGICAL YEAR

TOU: TIME OF USE

CHAPTER 1: INTRODUCTION

1.1 Poultry Demand in the U.S.

With the consistent growth of population and urbanization in the U.S., the food industry continues to expand and evolve to meet the consumer demand. Red meat and poultry consumption have increased by 1.8% every year on average since 2014 (CME 2021). Figure 1 shows the historical profiles of meat consumption per capita over the last 100 years (USDA 2021). It shows that chicken has been the highest meat consumption in the U.S. since 2010 and continues to rise.

Though broiler chickens account for a majority of the poultry industry in the U.S., raising

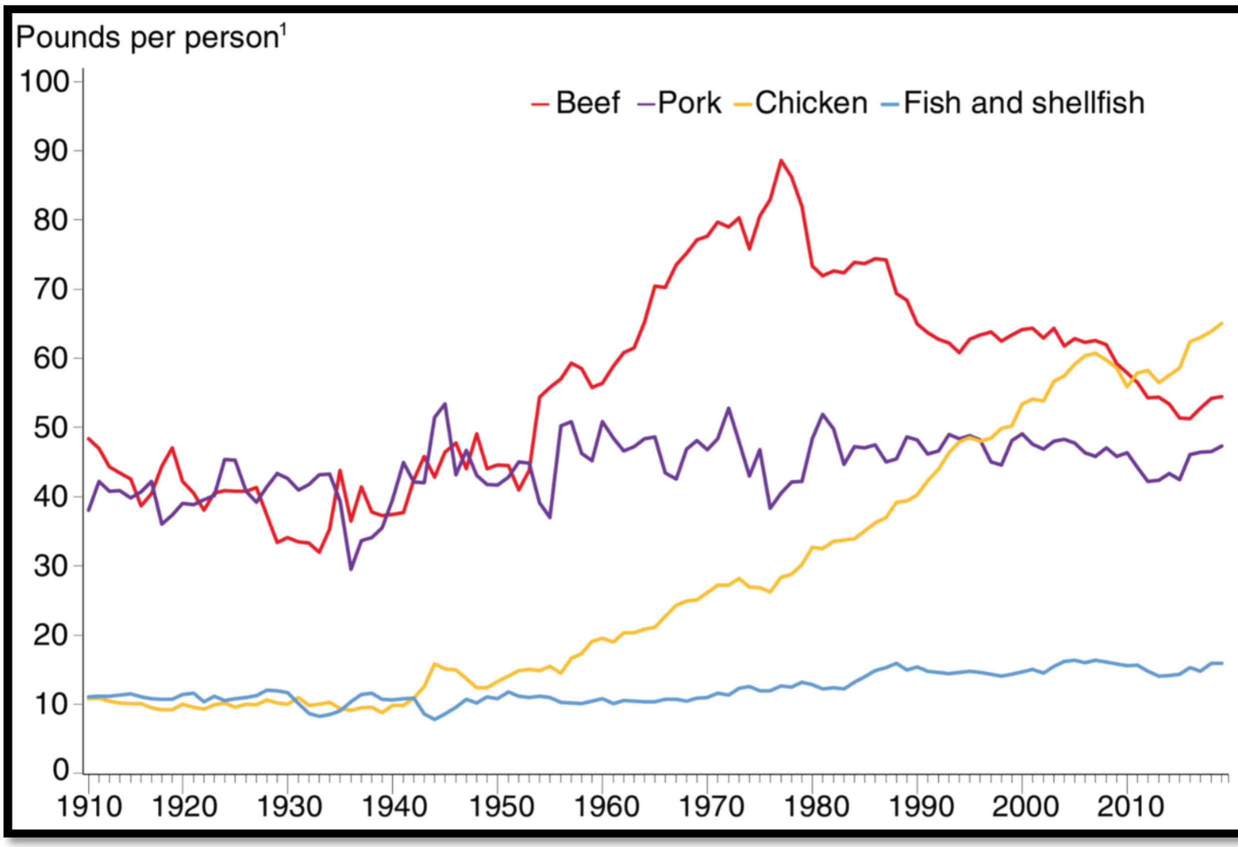

Figure 1: U.S. per capita availability of beef, pork, chicken, fish/shellfish - 1910-2018 (USDA 2021)

chickens for eggs is another important segment of the poultry industry. It was reported that from 1997 to 2017, the egg consumption in the U.S. had an average annual increase of 1.4% (FAO

2020). The eggs may come from table-egg farms or breeder farms. The table-egg farms produce eggs that are sold as shell eggs or are processed into products for foodservice while the breeder farms produce hatching eggs primarily for hatcheries.

1.2 Energy Consumption in Poultry Farms

Poultry farms require a significant amount of energy to maintain the appropriate living conditions for chickens. According to a study by Baxevanou *et al.* (2017), energy usage is greatly dependent on farm location, size of the houses, and the amount of chickens in the houses. For typical lowland farms the average electrical energy per flock weight is 0.12 kWh/kg and the average per house area is 24.23 kWh/m^2. The energy consumption of the poultry industry is expected to increase in the future to accommodate the growing demand of poultry products and the increasing attention to animal welfare.

The energy used in poultry farms is mainly for poultry house heating and cooling, ventilation, and lighting. In addition, energy is required for the feed lines, manure management, and the operation of farm machinery.

1.2.1 Heating and Cooling

Temperature regulation is crucial for the growth and health of poultry birds. Space heating is needed during the brooding phase to maintain comfortable temperatures for baby chickens while space cooling is needed on hot days to prevent heat stress, which is especially the case when the chickens are at the mature stage. Factors that affect the energy used for heating and cooling include the size of the poultry house, the thermal performance of the building envelope, the climate, and the type of heating and cooling equipment used (e.g., forced air heaters, radiant heaters, and evaporative coolers).

Heating and cooling are the largest energy end uses in poultry houses. Xin *et al*. (2009) examined the energy usage of broiler production facilities in the Midwestern United States and found that heating accounted for 61% of the total energy consumption, with an average energy use of 1,158 kWh per 1,000 birds per production cycle. The study also showed that the energy consumption for heating varied significantly depending on factors such as the insulation quality, the type of heating system, and the local climate conditions.

1.2.2 Ventilation

Ventilation is essential in poultry farms to maintain air quality, regulate temperature and humidity, and remove dust, ammonia, and carbon dioxide. The type of ventilation systems, such as natural ventilation, mechanical ventilation (including tunnel ventilation, cross ventilation, and negative pressure ventilation), and hybrid ventilation systems, affect energy consumption differently. Energy used for ventilation depends on the size and layout of the poultry house, the number of air exchanges per hour, and the fan efficiency. Purswell *et al*. (2012) found that ventilation accounted for 18% of the total energy consumption for broiler houses in the Southern United States.

1.2.3 Lighting

Lighting plays a significant role in poultry production, affecting the chicken growth, productivity, and behavior. Lighting lamps (e.g., incandescent, compact fluorescent, or LED), lighting schedules, and the intensity of light can affect the lighting energy consumption. Çalik *et al*. (2018) compared the energy usage of different lighting technologies in broiler production and found that LED lamps reduced energy consumption by up to 60% compared to incandescent lamps.

The study also highlighted the importance of lighting schedules and intensity to optimize energy consumption.

1.2.4 Feed and Water Supply

Automated feed and water supply systems are used in modern poultry farms to ensure the availability of food and water to the birds consistently. The energy consumption of these systems depends on the efficiency of the motors and pumps, the frequency of feed and water delivery, and the farm size. Gates et al. (2015) investigated the energy consumption of feed and water supply systems in broiler production and found that these systems accounted for approximately 9% of the total energy consumption.

1.2.5 Waste Management Systems

Waste management systems are used to manage poultry farm waste, including the removal, treatment, and disposal of manure and poultry mortality. Energy consumption on waste management is affected by the method used for manure removal (e.g., scraper systems or belt systems), the treatment processes involved (e.g., composting or anaerobic digestion), and the transportation of manure to disposal sites.

1.2.6 Other Farm Operations

Additional farm operations, such as egg collection, sorting, and packaging for layer farms or equipment maintenance and cleaning, can also contribute to energy consumption. The energy usage for these operations depends on the type of equipment used and the frequency of operation.

As such, the energy usage in poultry farms is significantly influenced by various load requirements due to poultry house heating and cooling, ventilation, lighting, feed and water supply, manure management, and other farm operations. Understanding the factors that have impact on these energy end uses is critical to implement energy-efficient technologies in poultry farms.

While it is important to minimize energy consumption and reduce emissions, power reliability is critical for poultry farms. If a power failure were to occur in a poultry house, many essential operations such as ventilation, water, and food supply could not function, and the consequence is disastrous. For example, it was reported that a farmer in Cleveland, NC lost around 60,000 birds in 2010 because one of the diesel generators failed to run during a power outage (Rivenbark 2010).

1.3 Research Questions

Poultry is the largest agricultural industry in North Carolina. For many poultry growers, energy cost is their second highest expense, right behind the house mortgages. Cutting utility bills via renewable energy generation on site is important to increase the profitability of poultry growers. There are increasing interests to deploy solar photovoltaics (PV) in poultry farms because of the following positive factors:

- The cost of PV systems has decreased significantly in recent years.
- There exist many incentives, rebates, and grants available from the federal, state and local governments and utility companies for renewable energy development.
- There are rarely space constraints on solar PV installation no matter whether the PV panels are roof- or ground-mounted; and
- Most locations in NC are abundant with solar resources.

On the other hand, because commercial poultry farms are located in rural areas that are served by electric cooperative (co-op), the policy on distributed solar is not so favorable to the customer as those offered by large utility companies. For example, net metering is not an option in the majority of electric co-ops and the price of power selling back to the grid is very low. There are also possibilities for renewable systems that use a combination of generation. Hybrid systems typically utilize at least one type of renewable generation along with energy storage and supplementary generation (diesel generator). Since most poultry farms are equipped with a generator on-site, the use of a hybrid system could become viable and it should be capable of handling the full system load for an extended period of time when needed. However, because a systematic study on the techno-economic analysis of solar PV and hybrid systems for poultry farms does not exist, the following research questions remain:

- Is solar PV investment on poultry farms profitable in current market situations? If not, what are the major factors that affect the profitability of PV investment?
- Will the combined use of battery storage and PV be more cost effective than the use of PV alone?
- Considering that all poultry farms have diesel generators sized to meet the full load, will it be economically making sense to use an off-grid PV-diesel-battery hybrid system? Regarding economics, how much difference does it have between the off-grid system and the grid-connected system?
- What is the optimal sizing of each major component of the PV-diesel-battery hybrid system? How does the optimal sizing change with different design conditions?

1.4 Research Methodology

This research aims to answer the questions raised in Section 1.3. For this purpose, the HOMER Pro microgrid software is used to simulate and optimize the PV-diesel-battery hybrid system for poultry farms which is a widely used simulation software and is discussed in Chapter 3. The electric load profile is based on the actual metered power with 15-minute intervals for a poultry farm in NC. Typical meteorological year data are used for solar radiation and ambient air temperature. A generic configuration is defined separately for grid-connected systems and off-grid systems. Major component sizes are then optimized using HOMER for different cases that vary with the utility rate structure and solar power compensation mechanisms. A full list of model inputs and output results are provided in APPENDIX: A. The optimal solutions are presented in tables and figures to compare different cases with respect to the optimal component sizes and the performance criterion (i.e., the net present cost). HOMER software is also used to perform the sensitivity analysis with component prices as the perturbed variables. The expected outcome is that the use of hybrid systems may offer more environmental benefits but the overall system cost will likely exceed that of normal farm operation. For grid-connected systems the inclusion of PV models will likely be a favorable options for some cases depending on utility rate structures. The expectations of this is to show multiple cases and variables so farms who may have interest in the topic can apply their situation to the results in this study and conclude if a PV or hybrid system investment would be worthwhile under the current market conditions.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview of Microgrids

A microgrid is any generation that services a local load that is able to function independently of a grid connection. As such, hybrid systems fall under the definition of a microgrid and so research into this field is conducted. Poultry farms are in a sense a microgrid as they have the ability to disconnect from the grid and supply their local load through the means of a diesel generator in times of power outages. This study aims to show the cost measures of adding on-site generation in the form of renewables to form a hybrid system microgrid farm. Microgrids are used in this study for their ability to aid in the performance and security of poultry farms.

Microgrids are localized energy generation and storage systems that can operate either grid-connected or standalone. Traditionally, they are often used in remote locations with no or unreliable access to the utility service. However, with the increasing penetration of distributed renewable energy systems, there is an expanded implementation of microgrids in territories covered by the grid network. A microgrid not only protects its customers during a power outage but also provides ancillary services (e.g., voltage and frequency control, congestion management and improvement of power quality) to the power grid. Typically, a microgrid contains a group of interconnected loads, one or more non-dispatchable renewable energy resources (e.g., solar panels and wind turbines), dispatchable energy sources (e.g., diesel generators), energy storage (e.g., battery) and controllers that can effectively management the real time operation of all components and to satisfy power demand and stable operating conditions. A grid-connected microgrid normally operates with connection to the power grid (referred to as the grid-connected mode), but it is able to disconnect from the grid and operate in the island mode. Due to most grid protocols, all distributed energy generation directly connected to the grid must be shut down in times of power outages as to not feed power back to the main grid (Asmus 2010). With microgrids, however, since they can be disconnected from the main grid, this allows for continuous running of on-site generation, something that is not an option with net metering. To implement a successful intentional island, the system should detect the islanding event as soon as the grid gets disconnected. Most solar systems are connected to the grid via a solar grid controller. This controller allows the utility company to track the amount of power sold back to the grid via a metering system, while also acting to stop production of the onsite generation in times of grid shutdowns.

Microgrids support a flexible, resilient, and efficient electric grid by enabling the integration of distributed energy sources. Because microgrids play an important role towards the realization of a smart and decarbonized grid in the United States, there are many studies, demonstrations, and support from federal and local governments. Feng *et al.* (2018) stated that around 34% of the world's microgrids are located in the US. The Department of Energy (DOE), more specifically, the Office of Electricity Delivery and Energy Reliability (OE), is the main agency promoting the research, development and deployment of microgrids in the US. Working together with the US Department of Defense, DOE funded the development of analysis tools, systems testing, and demonstration programs. The Renewable and Distributed Systems Integration program initiated by the OE in 2008 funded projects to incorporate the use of distributed energy generation. Later on, the OE spent more efforts on microgrid controllers and standards to enable speed deployment and reach the goal of reducing the number of outages by >98% (Feng *et al.* 2018). Currently, the Microgrid Installation Database (DOE 2023) includes a total of 461 operational grid-connected microgrids that provide a total of 3.1 gigawatts of reliable electricity in the US. When in connection with the power grid, it is important that the microgrid appear as a single synchronous generator, do not exceed line ratings, operate voltage and frequency levels within acceptable ranges, and dispatch resources to maintain energy balance (Hirsch *et al.* 2018).

Microgrids typically include energy storage to increase power reliability. Since microgrids service smaller loads the power fluctuation can vary greatly depending on what utilities are powered on. Because of this, energy storage is a vital part of microgrids as it offers stable power distribution to the load. Electrical storage can assist in voltage control, power consistency, and the increase of renewable fraction. Power inverters are important components in renewable microgrids because there is a need to convert from high frequency AC power to DC and vice versa. All-DC microgrids, which consist of DC-power generation (e.g., PV solar), DC storage, DC loads, and DC-DC power conditioners, offer opportunities for efficiency improvement by reducing the power losses associated with DC-AC conversions.

2.2 Review of PV Hybrid Systems

Solar PV is chosen as the renewable source in the hybrid system because it is a favorable renewable generation source. For this study they are promising since poultry farms are large there is no worry of space constraints as panels can be easily ground or roof mounted. PV is not considered to be a microgrid alone, since the generation is not consistent the load cannot be serviced at all times. In order for PV to be used as a microgrid other components such as controllers and energy storage must be used. PV hybrid systems are energy generation solutions that combine solar PV technology with one or more alternative energy sources or storage systems. These systems provide a more stable, reliable, and efficient power supply, addressing the intermittent nature of solar energy and ensuring continuous power availability (Deshmukh & Deshmukh, 2008). PV-diesel-battery hybrid systems would work well in a poultry farm application for the following reasons: The aforementioned positive for PV is no space constraints, battery storage would allow the energy generated to be storage and used in times of peak load, a diesel generator is already utilized in most poultry farms. This section provides an overview of PV hybrid systems, their components, and the benefits they offer, with scholarly sources to support the information provided.

2.2.1 Components of PV Hybrid Systems

The main components of a typical PV hybrid system include (Hossain et al., 2013; Deshmukh & Deshmukh, 2008):

- Solar PV panels. These panels convert sunlight into electricity using semiconductor materials (e.g., silicon). The DC electricity generated by the PV panels needs to be converted to AC using an inverter.
- Alternative energy sources. PV hybrid systems often integrate other energy sources to compensate for the intermittent nature of solar power. These sources may include wind turbines, diesel generators, or other renewable energy technologies such as hydroelectric or biomass power.
- Energy storage. To enhance power stability and ensure continuous power supply, PV hybrid systems often include energy storage systems (e.g., battery and pumped hydro storage). These systems store excess energy generated during peak sunlight hours and release it when solar energy production is low, or demand is high.
- Inverter. The inverter is part of the balance-of-system, it is responsible for converting the DC power generated by the PV panels and battery into AC power suitable for use in electrical appliances and systems.

- Charge controller. Another part of balance-of-system is the charge controller, which regulates the charging and discharging of the energy storage systems to prevent overcharging or deep discharging, which can reduce battery life and efficiency.

2.2.2 Benefits of PV Hybrid Systems

Hazelton *et al.* (2014) offer some insight as to why PV hybrid systems can offer several benefits compared to standalone solar PV and conventional energy generation systems:

- Improved power stability. By combining solar PV with other energy sources and storage systems, PV hybrid systems provide a more stable power supply, mitigating the intermittent nature of solar energy.
- Enhanced power reliability. PV hybrid systems enable continuous power availability, even during periods of low solar energy production or grid disruptions, making them suitable for remote or off-grid applications.
- Energy cost savings. By generating power from renewable sources like solar and wind, PV hybrid systems can reduce the reliance on grid electricity or fossil fuel-based power generation, leading to potential energy cost savings.
- Environmental benefits. PV hybrid systems that rely on renewable energy sources produce less greenhouse gas emissions and have a lower environmental impact than conventional energy generation systems.
- Scalability and flexibility. PV hybrid systems can be easily scaled up or down to meet varying energy demands and can be adapted to incorporate new energy technologies, making them a versatile solution for various applications.

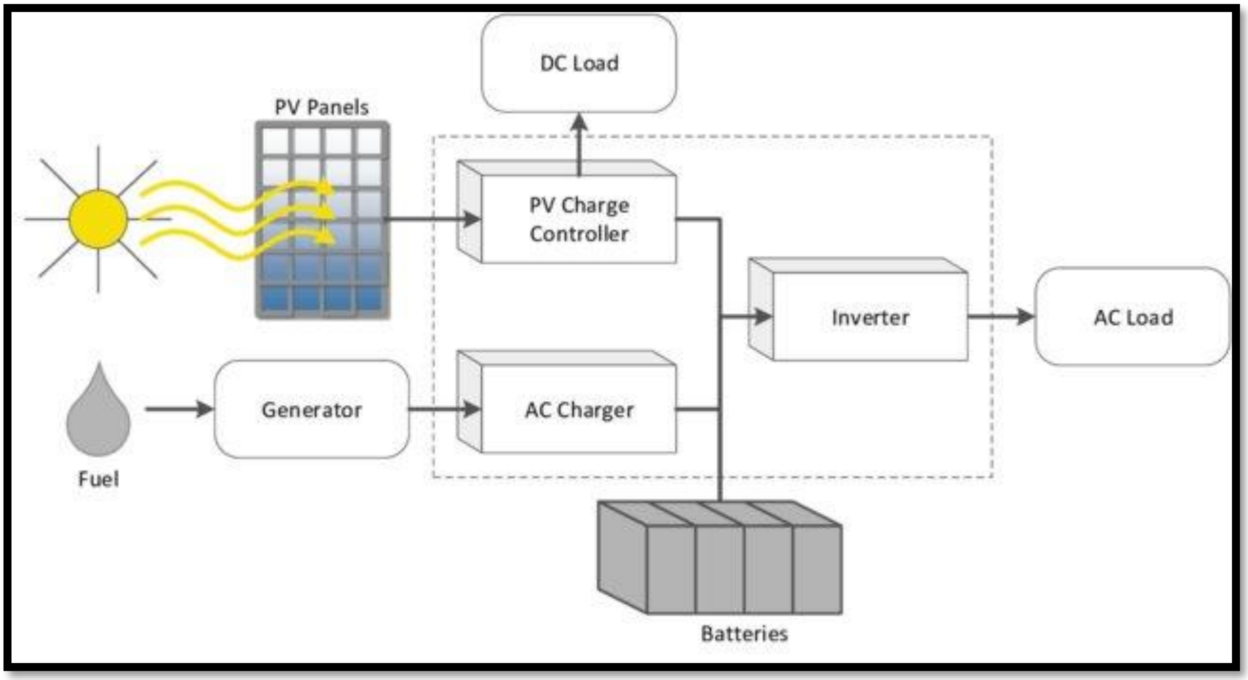

Figure 2: PV-diesel-battery hybrid system components (PVPs, 2015)

Overall, PV hybrid systems are potentially an effective solution for addressing the challenges of solar energy intermittent and ensuring a stable and reliable power supply. By combining solar PV technology with other energy sources and storage systems, these systems provide numerous benefits, including improved power stability, enhanced reliability, and a reduced environmental impact.

2.2.3 Literature on PV Hybrid Systems

Rezzouk and Mellit (2015) studied the use and feasibility of a PV-diesel hybrid system deployed in northern Algeria, they considered the options ranging from 100% PV penetration to 100% diesel penetration. The goal was to find the optimal penetration of the two generations that yield the greatest efficiency, lowest energy costs, and best system stability. HOMER software was used to compare the optimal configurations of a PV-diesel-battery energy system with three different PV penetrations (i.e., 25%, 50%, and 75%), a standalone diesel system, and standalone

PV power generation system. The simulation results showed that a hybrid system of 25% PV and 75% diesel yielded the best production results based on the net present cost and levelized cost of electricity (Rezzouk and Mellit 2015).

Das and Zaman (2019) conducted a performance analysis of a standalone PV-diesel-battery hybrid system in a remote community in Bangladesh. The focus was to compare the effects of different dispatch strategies on the cost of energy and the net present cost using two energy storage technologies: lead-acid battery and lithium-ion battery. HOMER software was used in this analysis. The results indicated that the combined dispatch strategy had a slightly lower cost of energy than the load following and cycle charging strategies.

Cai *et al.* (2020) proposed a framework to determine the optimal sizing and location for off-grid PV-diesel-battery systems. In this framework, a geographic information system module was utilized to identify the best location based on the technical, economic, reliability, social, and environmental criteria. Then, based on the mathematical models of the components of the hybrid system, they combined the use of simulated annealing and harmony search optimization algorithms to determine the appropriate capacity for continuously meeting of the load via total life cycle cost minimization. The framework was tested with a real case study in South Khorasan, Iran to illustrate its effectiveness.

Çetinbaş *et al.* (2019) presented the design, performance analysis, and optimization of a grid-connected PV-diesel-battery microgrid for a hospital complex using the HOMER software. The focus was to obtain reliable data from the microgrid design by considering PV module failures, increase in electric loads, increase in fuel cost of diesel generators and main power interruptions, all of which were important factors to consider over the 25-years of service time. Appling these factors to the base microgrid design could increase the net present cost (NPC) by 40%, the levelized cost of electricity (LCOE) by 22%, and the operating cost by 54%.

Khan *et al*. (2017) investigated the techno-economic feasibility of different combinations of PV, wind, diesel, and battery hybrid systems for telecommunication applications in various cities in Punjab, India. The authors aimed to determine the optimal configuration of hybrid systems to provide reliable, cost-effective, and environmentally friendly energy solutions for powering telecommunication infrastructure in the region. They used HOMER software to simulate and analyze the performance of various hybrid system configurations. The optimization objective was to minimize the LCOE while ensuring the reliability and stability of the power supply for telecommunication systems.

Shaahid and El-Amin (2009) conducted a techno-economic evaluation of off-grid hybrid PV, diesel, and battery power systems for rural electrification in Saudi Arabia. The authors aimed to assess the feasibility of these hybrid systems as a sustainable and cost-effective solution for meeting the energy needs of remote areas in the country while reducing greenhouse gas emissions and promoting sustainable development. HOMER software was used to model and analyze the performance of various hybrid system configurations, considering local solar radiation data, diesel fuel prices, and other relevant factors. The optimization objective was to minimize the LCOE while ensuring reliable power supply for the target rural communities. The study found that hybrid PV-diesel-battery systems were a feasible and economically viable option for rural electrification in Saudi Arabia. The optimal system configuration varied depending on the size of the community and its electricity demand.

Hrayshat (2009) did a techno-economic analysis of autonomous hybrid systems that utilized a PV-diesel-battery setup to determine its effectiveness in meeting the load of an off-grid house. Using electrical load data and solar data for the area he was looking to implement he used HOMER software to optimize the hybrid system model. The objective was to find if the use of a hybrid system was more effective than simply supplying all power from diesel generation. The results showed that the use of a hybrid system was viable with diesel prices over 0.15 $/L.

Usman *et al*. (2018) researched the optimization of several hybrid energy systems in India. The system models consisted of PV, diesel, and grid connection and optimization was based on techno-economics of the systems renewables through the use of HOMER software. They obtained load profiles, solar data, and defined system components and specifications and created models in HOMER for optimization. Their findings indicated that the implementation of PV could be a feasible solution, however, the use of a hybrid system showed an initial cost factor which was too high to be considered as a viable solution.

The research done provides insight into the methods used for techno-economic analysis of hybrid systems. These studies done on hybrid systems show use of hybrid systems in various locations with differing parameters and loads, however, the methodology for conducting the analysis is relevant for this topic. The studies utilized HOMER to find optimal system sizes and architecture for the best NPC and determined whether the system was feasible. This is applicable to this study since determining if a hybrid system is economically feasible is a primary aspect.

2.3 Literature on Renewables in Poultry Farming

Bazen and Matthew (2009) conducted a case study on the advantages and limitations of utilizing solar PV within Tennessee's poultry industry. Their goal was to determine the economic feasibility of solar PV adoption by assessing the impact of alternative energy programs, grants, and incentives available. The results showed that the use of solar PV was not economical at the time of their study. However, the conclusion is unlikely valid at the present time because of the dramatic decrease of PV cost.

Amadi *et al.* (2021) used HOMER to improve the PV system configuration for poultry farm operations. Based on the data (e.g., solar irradiation, ambient temperature, and energy demand) for a specific farm, they compared three system designs: a PV-battery system, a diesel generator only system, and a PV-diesel hybrid system. The PV battery system had 100% renewable penetration but it required a very large battery bank which made the system the most expensive one. The diesel generator system ranked second in terms of the cost but it had the highest emissions. The PV-diesel hybrid system had the lowest cost and less emissions than the diesel generator only system.

2.4 Overview of Solar Policy by Electricity Providers

In the US, there are many different types of electricity providers, about half of which are known as co-ops and municipals (munis). Co-ops function from a consumer-owned basis while munis are typically owned by the city or county where they reside. Both co-ops and munis serve the general public and operate from a board of directors that are publicly appointed. Co-ops typically serve to extend the grid to the rural parts of the country while minus serve smaller cities. Aside from these utility providers, there are investor-owned utilities (IOUs), which are typically companies that have monopolized areas. While there are far more muni and co-op companies around the nation, the majority of the consumers are served by IOUs. All these electricity providers are regulated by utility commissions that are state-appointed officials to oversee utility operations (GridFabric 2020).

In North Carolina, there are currently 3 IOUs, 32 electric co-ops, and 50 smaller munis (NCUC 2021). The three IOUs are Dominion North Carolina Power, Duke Energy Carolinas, and Duke Energy Progress.

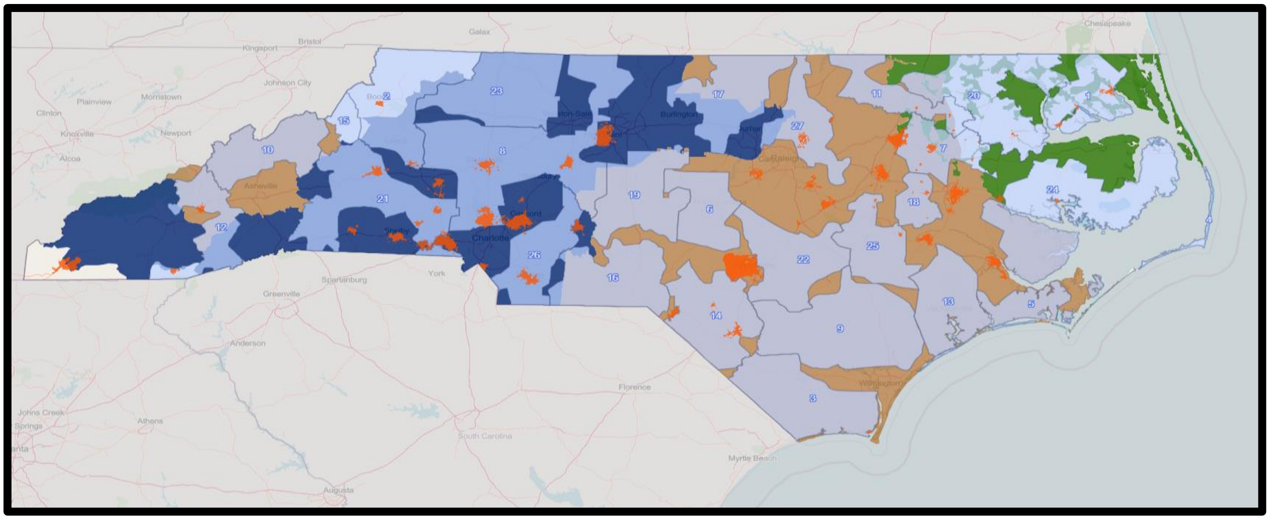

Figure 3: NC Electric Utility Providers Map (NCSEA 2021)

In Figure 3, the areas in orange, light blue, green, darker blue and brown represent the territory served by municipally owned electric utilities, the electric cooperatives, Dominion Power, Duke Energy Carolinas, and Duke Energy Progress, respectively. Different shades of light blue indicate which IOU supply the wholesale power to the co-ops. In addition, this figure shows that densely populated areas in the state are mostly served by the three main IOUs while the small towns and rural areas are served by the munis and co-ops.

In NC, poultry farms are served by either electric co-ops or IOUs, with the former being the predominant one. IOUs are more open to distributed solar development than co-ops as can be seen from the compensation mechanisms they offer. IOUs offer net energy metering, but most co-ops offer buy-all and sell-all. In addition to net metering and buy-all and sell-all, net billing is another compensation mechanism though it is rarely offered by NC electricity providers at the present time. These three compensation mechanisms (Zinaman *et al*. 2017) are briefly discussed in the following because they are heavily referred to in the next two chapters.

Net metering allows the customers to offset the electricity from the grid with the electricity generated onsite throughout the billing cycle (which is typically a month). If the onsite power generation is not sufficient to meet the demand, electricity is imported from the grid. If the onsite power generation exceeds the demand, the excess amount of electricity is exported to the grid. At the end of the billing cycle, the customer is billed for the net energy consumption, which is equal to the amount of imported electricity minus the exported electricity. If the net energy consumption is positive, the customer pays at the full retail rate for that electricity. Otherwise, the customer may receive a credit (either in kWh or dollars) that can be used in future billing cycles.

Buy-all-sell-all (BASA) does not allow the customers to consume the electricity generated onsite. The customer is billed for all electricity consumption at the retail rate. Meanwhile, all onsite electricity generation is exported to the grid and the customer is paid at a predetermined sell rate, which is typically much lower than the retail rate. Net billing allows the customers to consume the electricity generated onsite in real time. However, the excess electricity exported to the gird cannot be used to offset the energy consumption in the billing cycle. Instead, all net energy exports are metered and credited at a predetermined sell rate.

Since poultry farms are often located in rural areas, they are largely serviced by co-ops and municipals. The policies offered by these businesses are crucial in determining if a solar investment will be feasible. Generally, net metering is the most favorable compensation mechanism for distributed solar generation while buy-all and sell-all is the least favorable compensation mechanism. These different policies will be used in the study as variables for different system models. This will allow different policy scenarios to be analyzed as well as to find which is the most favorable for solar investment.

CHAPTER 3: SYSTEM CONFIGURATION AND SIMULATION

This chapter starts with a description of the PV-diesel-battery hybrid system configurations. Then, the HOMER software used to simulate and optimize the systems is briefly discussed. The electrical load profile of the poultry farm considered in the simulation study and the meteorological data needed by the simulation are presented. The last section of this chapter devotes to the description of the physical modeling and the simulation inputs of the hybrid system components.

3.1 System Configurations

A hybrid system is characterized by combining one or more renewable energy (e.g., solar, wind, and biomass sources) with other technologies such as battery storage and diesel generators. As one of the most common hybrid systems, a PV-diesel-battery hybrid system couples PV, diesel generators (also known as diesel gensets) and battery storage to satisfy the power demand. This work investigates two PV-diesel-battery hybrid system configurations: a grid-connected hybrid system (Figure 4) and a standalone off-grid hybrid system (Figure 5).

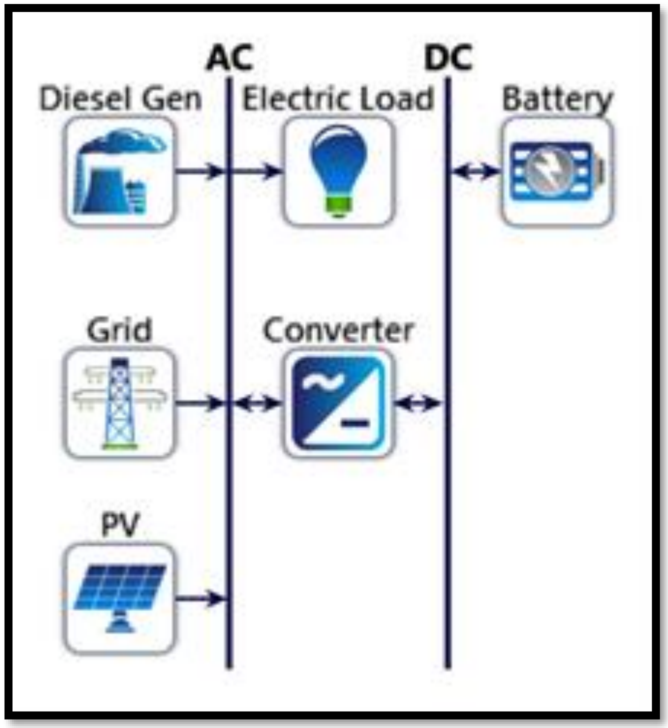

Figure 4: Grid-connected model

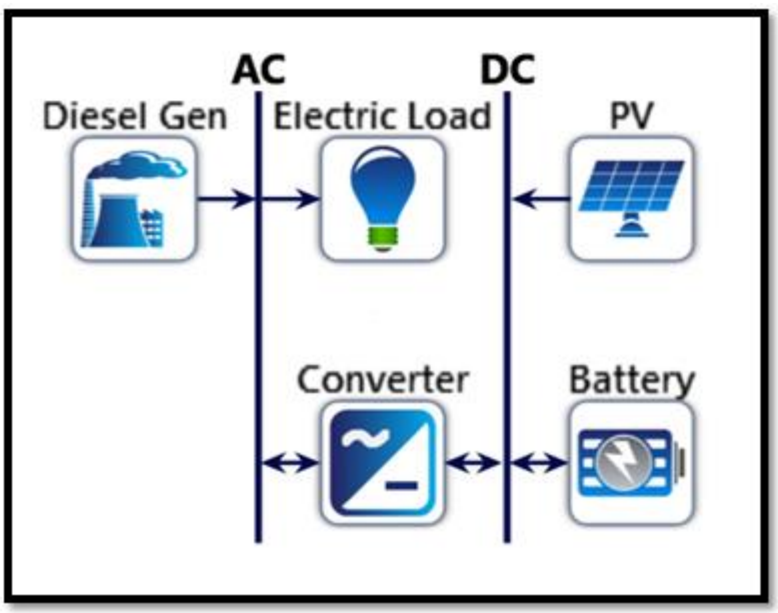

Figure 5: PV-diesel-battery hybrid system model schematic

In the grid-connected system, the battery is AC-coupled. The system requires two inverters: one grid-tied, unidirectional inverter for the PV array and one bidirectional battery-based inverter.

When used by the electrical load or exporting to the grid, the PV power just needs to be converted from DC to AC through the grid-tied inverter. However, when used to charge the battery, PV power is converted from DC to AC through the grid-tied inverter and then converted from AC to DC through the battery-based inverter. The efficiencies of each of the conversion methods will be considered in the form of inputs for the models.

In the standalone off-grid system, the battery is DC-coupled. The system requires a charge controller that is used to step down the PV output voltage to a level safe for the battery and a single bidirectional inverter that is tied to both the PV array and the battery. When used for the load or exporting to the grid, PV power needs to pass through the charge controller and the inverter. However, when used to charge the battery, PV power just needs to pass through the DC-DC charge controller. Through this method the battery can also be charged by the diesel generator.

In general, the AC-coupled system is more efficient in applications where the PV energy is directly used by the electrical load at the time of generation while the DC-coupled system is more efficient in applications where the PV energy is stored at the time of generation and then used later (Ardani *et al*. 2017). The PV energy, if available, is mostly used for loads in the grid-connected system, which is why the AC-coupled configuration is used. Similarly, the PV energy is expected to be used for both loads and battery storage in the standalone off-grid system, which is why the DC-coupled configuration is used.

3.2 HOMER Software Description

Sinha and Chandel (2014) reviewed 19 software tools for the design, analysis, optimization, and economic viability of hybrid renewable energy systems. This included software such as HOMER, HYBRID 2, HYBRID DESIGNER, SOLSIM, and HySim. They found that while many of the programs had similar functionality, HOMER was the most widely used tool because of its many favorable features such as the flexibility of technology options and the ease of use. HOMER is used for this study as it is proficient in finding feasible systems and optimizing for lowest NPC. It also provides the ability investigate the change of system performance from varying a number of input parameters (e.g., the component cost and the utility rates) via sensitivity analysis.

Originally developed by NREL in the 1990s, HOMER is now part of UL Solutions, and it now comes in different software versions HOMER Pro, HOMER Grid, and HOMER Front. HOMER Pro can model both grid-connected and off-grid hybrid systems but specializes in use for off-grid systems. Currently, HOMER Pro supports 10 components:

- Three non-dispatchable and renewable power sources: PV modules, wind turbines, and run-of-river hydro turbines.
- Three dispatchable energy sources: diesel generators, the power grid, and boilers.
- Two components that convert electrical energy into another form: bi-directional power inverters that convert between AC and DC and electrolyzers that convert from electricity to hydrogen.
- Two energy storage components: batteries and hydrogen storage tanks.

This research uses five components (i.e., PV module, diesel generator, the power grid, battery, and power inverter) with their modeling and simulation inputs to be described in Section 3.5.

HOMER offers three core capabilities: simulation, optimization, and sensitivity analysis. As the basis of optimization and sensitivity analysis, HOMER’s time-series simulation is performed for a particular system with a specific configuration (i.e., which components are included), the specific sizes of all components, and a specific operating strategy that defines how the components work together. The simulation serves two major purposes (Lambert *et al*. 2006). The first purpose is to determine whether the simulated system is a feasible solution. A system is feasible if it can satisfy the loads without violating any user-defined constraints, such as the minimum renewable fraction and maximum annual capacity shortage. The second purpose is to calculate the total net present cost (NPC) of the system. HOMER calculates NPC with the following equation:

$$NPC = \frac{AC}{CRF(i,n)} \quad (1)$$

Where, AC represents the annualized cost ($) of the system, and CRF is the capital recovery factor depending on the real discount rate (i) and the project life (n) in years. The values of $i = 6.1\%$ and $n = 25$, sourced from Ramasamy *et al*. (2022) is used in this research. The value of 25 years is used because of its correlation to typical lifetime of PV panels, and the real discount rate considers average values for nominal discount rates and interest rates.

The annualized cost (AC) is the total annual cost of owning, operating, and maintaining the system over its entire life. The system's total AC is the sum of the AC of all components. For each component, the AC considers costs associated with the initial capital investment, replacement, operation and maintenance (O&M), fuel, the salvage value and possible revenues. The capital recovery factor is given by:

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

Where the variables *i* and *n* are defined earlier. The purpose of HOMER's optimization is to determine the optimal value of each decision variable. Decision variables that are considered by HOMER and relevant to this study include the PV array size (i.e., rated capacity in kW), the number of batteries, the inverter size, and the dispatch strategy. The optimization algorithm is proprietary and thus no details are available.

HOMER conducts sensitivity analysis by performing many optimizations, each of which uses a different set of perturbed inputs. In HOMER, almost every numerical input that is not a decision variable can be treated as a sensitivity variable. Therefore, HOMER is capable of performing sensitivity analysis for numerous inputs such as the fuel price, the capital cost of any component, and the component lifetime. Because each combination of sensitivity variable values is an optimization case, defining a large number of sensitivity variables or a large number of perturbed input values for a sensitivity variable will significantly increase the computation time.

3.3 Electrical Load Profile

The load data is based on a real poultry farm located in NC. This farm raises broiler chickens, and it has three mega-size poultry houses (183m x 18m). The load data is in 15-min intervals for the whole year in 2020. Because the original data is in kWh and there are some missing values, the data file is preprocessed before its use in HOMER by converting from kWh to kW and filling out the missing values. Table 1 lists several statistical metrics of the electrical load profile. Figure 6 shows the monthly box and whisker plots, and Figure 7 shows the frequency histogram of the electrical load.

Table 1: Statistical metrics of the annual electrical load profile

Statistical Metrics	**Value**
Annual electricity consumption (kWh)	264,035
Average electrical load (kW)	30.14
Peak electrical load (kW)	108.8
Day-to-day coefficient of variation (%)	69.5
Time-step-to-time-step coefficient of variation (%)	35.7

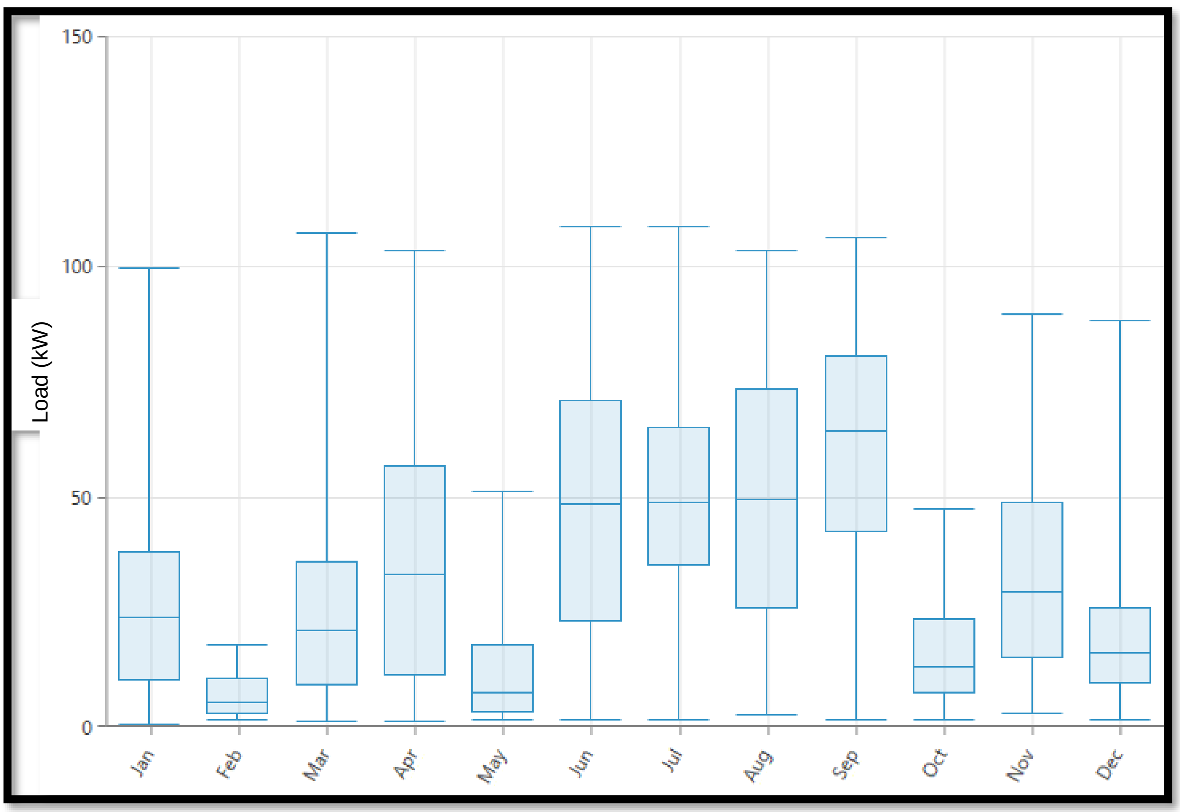

Figure 6: Monthly box and whisker plots of the electrical load profile

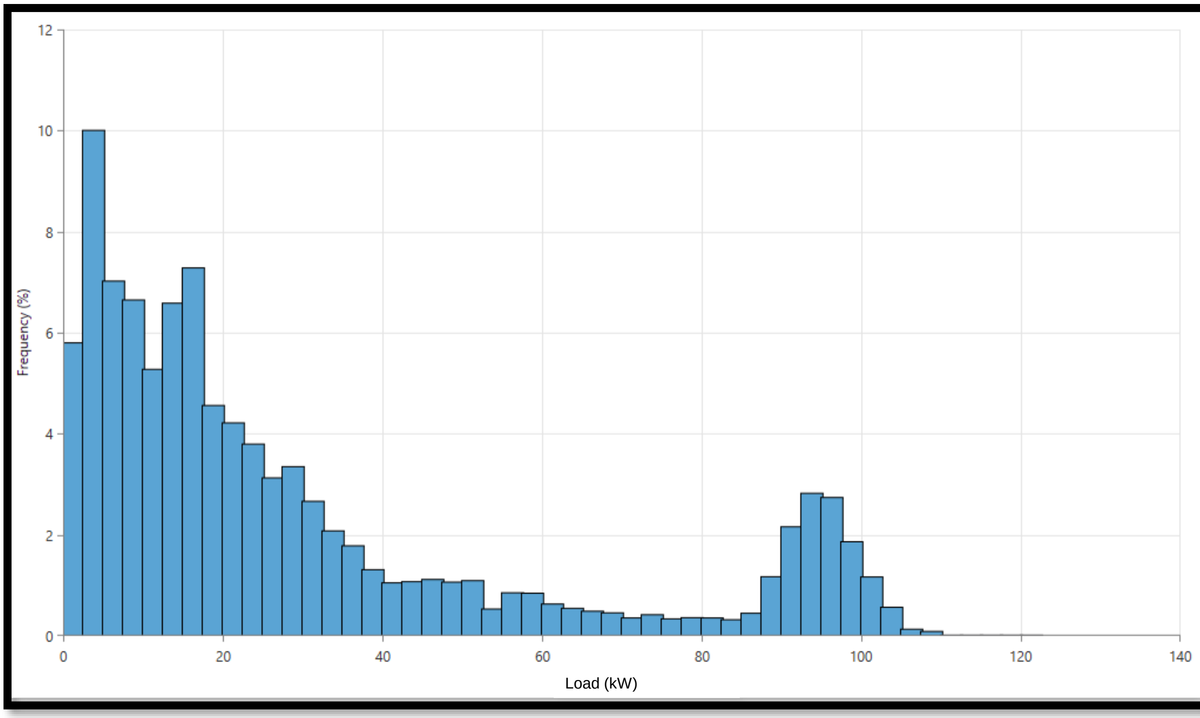

Figure 7: The frequency histogram of the annual electrical load with 15-minute intervals

As illustrated in Figures 6 and 7, the electrical load has a high variability. Most of the variability is attributed to the weather and flock schedules. At the beginning of each flock, small chickens need minimal ventilation for moisture and air quality management. However, as the flock progresses and the chickens grow up, more ventilation is needed which causes higher electrical load from fan running.

3.4 Meteorological Data

As will be discussed later, HOMER needs global horizontal irradiance (GHI), and ambient air temperature for PV modeling. Both GHI and air temperature are obtained from the National Solar Radiation Database (NSRDB) maintained by NREL (2022). Typical Meteorological Year (TMY) data are derived from the NSRDB time-series datasets from 1998 to 2020. The TMY dataset contains one year of hourly data that best represents the weather conditions over a multiyear period for the specific location considered in this study—Statesville, NC. Based on the TMY data, Figure 8 shows the monthly average global horizontal solar radiation and ambient air temperature.

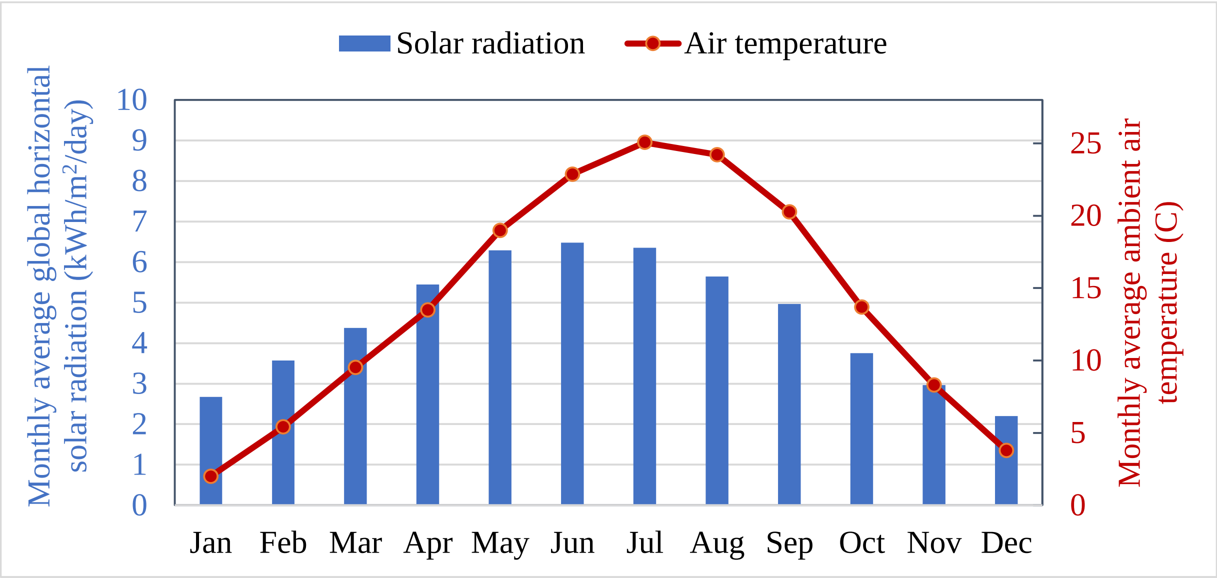

Figure 8: Monthly average global horizontal solar radiation and ambient air temperature based on the Typical Meteorological Year data for Statesville, NC.

3.5 Component Modeling and Input Parameters

3.5.1 PV Modules

HOMER calculates the power output of PV modules with the following equation:

$$P_{PV} = Y_{PV} f_{PV} G_T [1 + \mu (T_c - 25)] \quad (3)$$

Where,

P_{PV}: Power output of the PV modules (kW)

Y_{PV}: Rated PV capacity under Standard Test Conditions (kW)

f_{PV}: PV derating factor (%)

G_T: Solar irradiance on the PV (kW/m^2)

μ: Temperature coefficient of PV power output (%/(°C))

T_c: PV cell temperature (°C)

HOMER defines an energy balance for the PV array using an anisotropic sky model (Duffie and Beckman 1991) to calculate the solar irradiance G_T on the tilted surface of PV modules. The model has the following equation:

$$G_T = (G_b + G_d A_i)R_b + G_d(1 - A_i)\left(\frac{1+cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + G\,\rho_g\left(\frac{1-cos\beta}{2}\right) \quad (4)$$

Where,

G: the global horizontal irradiance (kW/m2), which is available from the weather file (Section 3.4).

G_b: the beam component of the global horizontal irradiance (kW/m^2)

G_d: the diffuse component of the global horizontal irradiance (kW/m^2)

R_b: the geometric factor that indicates the ratio of beam radiation on the tilted surface to that on a horizontal surface.

A_i: the anisotropy index that indicates the atmospheric transmittance of beam radiation. It is estimated by the ratio between G_b and the extraterrestrial solar irradiance on a horizontal surface.

f: the factor used to account for horizon brightening (i.e., the diffuse radiation comes from the horizon). It is calculated as G_b/G.

β: the slope of PV modules (°), which is a user input parameter.

ρ_g: the ground reflectance, which is a user input parameter.

Based on the global horizontal irradiance provided as the time-series inputs, HOMER calculates G_b and G_d according to the correlation of Erbs *et al.* (1982), the details of which are not presented here.

In Equation 5, the PV cell temperature (T_c) is calculated as:

$$T_c = \frac{T_a + (NOCT - 20)\left(\frac{G_T}{0.8}\right)[1 - \frac{\eta(1-25\ \mu)}{\tau\alpha}]}{1 + (NOCT - 20)(\frac{G_T}{0.8})(\frac{\mu\eta}{\tau\alpha})} \qquad (5)$$

Where:

T_a: Ambient temperature (°C)

$NOCT$: Nominal operating cell temperature (°C)

η: Rated electrical efficiency of PV modules

T_c: The PV cell temperature (°C)

In this work, the rated PV capacity (Y_{PV}) is dealt as a variable to be optimized by HOMER. Table 2 lists the technical parameters and their values used for modeling the fixed PV systems.

Table 2: Technical parameters and their values for modeling PV modules

Parameter	Value	Source
Derating factor, f_{PV} (%)	86	Ramasamy *et al.* 2022
Ground reflectance, ρ_g (%)	20	HOMER 2023
Panel azimuth	0	Design convention
Panel slope, β (°)	20	Design convention
Temperature coefficient, μ (%/°C)	-0.45	Sun *et al.* 2021
NOCT (°C)	45	Sun *et al.* 2021
Rated electrical efficiency of PV modules at STC, η (%)	20.3	Ramasamy *et al.* 2022

In Table 2, the derating factor accounts for the losses of PV energy generation due to many real-world operating factors such as soiling, shading, mismatches, wiring, connections, and availability. Based on the PVWatts Calculator (NREL 2022), the value of 86% is used for the derating factor. According to HOMER (2022), the ground reflectance of 20% represents the average reflectance value for grass-covered environments. Both panel orientation (south- oriented, azimuth = 0) and slope (20°) are typical PV installations for locations without space constraints. The temperature coefficient of PV power generation and the nominal operating cell temperature (NOCT) are based on the study by Sun *et al. (*2021) and they have typical values for many commercial c-Si based PV modules. The rated module efficiency is set to 20.3% (Ramasamy *et al.* 2022), which is consistent with the surveyed results by Barbose *et al*. (2022). It is worth nothing that the PV module efficiency is merely used in Eq. 5 to calculate the cell temperature and it has therefore only minor impact on the simulation results.

The economic parameters of PV modules include the lifetime, the capital cost, and the O&M cost. PV panels are estimated to last about 25-30 years. Therefore, the value of 25 years (Sangwongwanich *et al.* 2018) is used in this study. Both capital cost and O&M cost refer to the cost for the entire PV system, including solar panels, the structural balance of system (BOS), the electrical BOS, and soft costs related to site preparation, permitting, inspection, and interconnection, installation labor, financing, engineering, procurement, and construction (EPC) overhead and profit. Actually, the PV modules only account for a small portion (~20%) of the system cost. There are many different sources of PV system cost. For example, both NREL (Ramasamy *et. al.* 2022) and LBNL (Barbose *et. al.* 2022) have published reports on PV system cost regularly. The NREL study uses a bottom-up approach to estimate the cost for representative systems, including a 7.9-kW residential rooftop PV system, a 200-kW commercial rooftop PV system, a 500-kW commercial ground mount PV system, and a 100-MW utility scale one-axis tracking PV system. In contrast, the LBNL study provides the statistical data of the installed price (i.e., the price paid by the PV system owner), and other characteristics based on a large sample of real projects. The LBNL study classifies the PV systems into residential, small non-residential (≤100 kW DC) and large non-residential (>100 kW DC). Table 3 summarizes the capital costs of commercial standalone PV systems from the NREL and LBNL studies.

Table 3: Cost of installed PV systems based on size (Ramasamy *et al*. 2022) (Barbose *et al*. 2022).

Data source	System size (kW DC)	Capital cost ($/W DC)	
		National average	NC state
NREL	200	1.63	NA
LBNL	Small non-residential (≤100 kW)	3.0 (median) 2.3 (20th percentile) 4.1 (80th percentile)	2.8 (median) 2.2 (20th percentile) 3.7 (80th percentile)
	Large non-residential (>100 kW)	2.0 (median) 1.6 (20th percentile) 2.9 (80th percentile)	1.5 (median) 1.2 (20th percentile) 2.0 (80th percentile)

With the LBNL study for price of PV, it is important to determine the price per watt that the system would cost dependent of the total size of the system. From the study done by LBNL they provide some different pricing results that correspond to various system sizes shown in the table below.

Table 4: LBNL PV system price blocks (Barbose *et al*. 2022).

Source	System Size (kW)	Capital Cost ($/$W_{DC}$) National Average
LBNL	≤ 10	3.6
LBNL	10-20.	3.1
LBNL	20-50	2.7
LBNL	50-100	2.6
LBNL	100-250	2.2
LBNL	250-500	2
LBNL	500-1,000	1.8

Values in Table 4 will be used directly with other PV price variables in the HOMER software so the correct price for PV can be calculated based off the system size.

The prices of installed PV in Table 4 do not consider any incentives. In this study the PV price will be considered along with the federal incentives offered to renewable energy systems. In order to calculate the benefit of federal incentives for the use of HOMER optimization, the incentives and deductions must be considered prior to the input of the price in HOMER Pro. This means that the price blocks were altered to consider the added benefit of the incentives and then the final calculated price for each system size block was used. Available federal incentives lead to the reduction of PV system cost by 47.3% (APPENDIX: B). There are also savings on overall cost that can be considered when purchasing and installing a PV and battery system together. Barbose *et al*. (2022) indicated that the cost of a PV plus battery system could be 20% less than the total cost if PV and battery are installed separately. .

The O&M cost of PV modules is estimated at an average 17 $/kW/year (Walker *et. al.* 2020). This cost includes preventative maintenance scheduled at regular intervals and corrective maintenance to replace defective components.

3.5.2 Battery Storage

HOMER offers three types of models that are commonly used for battery energy storage: 1) an idealized storage model that assumes the capacity does not change with the charge or discharge rates; 2) a kinetic battery model that calculates the limits of power charging or discharging depending on the battery state; and 3) an advanced kinetic battery model that is based on the kinetic battery model but with additional considerations of temperature effects and degradation of performance over the lifetime. The kinetic battery model is used because it has a good balance between data availability and model accuracy.

The kinetic battery model (Manwell and McGowan 1993) is based on a chemical kinetics process to simulate battery charging and discharging. The model assumes that the battery charge is split into two tanks: one for available charge and the other for bound charge. The tank for available charge can supply electrons directly to the load while the tank for chemically bound charge can only supply electrons to the available-charge tank. Modeling the kinetic process needs three parameters:

- Q_{max}: the maximum storage capacity (kWh) that the two tanks can contain.
- c: the ratio of the available energy tank size to the combined size of both tanks.
- k: the conductance between the two tanks measuring how quickly the storage can convert bound energy to available energy or vice versa. It has the unit of 1/hr.

Based on the above three parameters, the maximum amount of power for charging and discharging over a specific length of time step is calculated by Eq. 6 and Eq. 7, respectively (HOMER 2022):

$$P_{cmax,kbm} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{6}$$

$$P_{dmax,kbm} = \frac{kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \tag{7}$$

Where,

$P_{cmax,kbm}$: the maximum power for charging (kWh), taking negative values.

$P_{dmax,kbm}$: the maximum power for discharging (kWh), taking positive values.

Q_1: the amount of available energy at the beginning of the time step (kWh)

Q_2: the amount of bound energy at the beginning of the time step (kWh)

Q: the total amount of energy at the beginning of the time step (kWh), $Q = Q_1 + Q_2$

Δt: the length of the time step (hr)

In addition to the maximum power for charging and discharging based on the chemical kinetics, HOMER also sets the power limit related to the maximum charge current and the maximum discharge current according to the following two equations (HOMER 2022):

$$P_{cmax,mcc} = \frac{-I_{cmax}V_{nom}}{1000} \quad (8)$$

$$P_{dmax,mdc} = \frac{I_{dmax}V_{nom}}{1000} \quad (9)$$

Where,

$P_{cmax,mcc}$: the maximum power for charging corresponding to the charge current limit (kWh)

$P_{dmax,mdc}$: the maximum power for discharging corresponding to the discharge current limit (kWh)

I_{cmax}: the absolute value of the maximum charge current (A)

I_{dmax}: the absolute value of the maximum discharge current (A)

V_{nom}: the nominal voltage of the battery storage (V)

Therefore, at each time step, the maximum charge power after accounting for charging losses is given as:

$$P_{cmax} = \max\left(P_{cmax,kbm}, P_{cmax,mcc}\right) \quad (10)$$

Similarly, the maximum discharge power prior to accounting for discharging losses is given as:

$$P_{dmax} = \min\left(P_{dmax,kbm}, P_{dmax,mdc}\right) \tag{11}$$

After HOMER calculates the actual charge or discharge power at each time step, the available energy and bound energy at the end of the time step are calculated using the following two equations (HOMER 2022):

$$Q_{1,new} = Q_1 e^{-k\Delta t} + \frac{(Qkc-P)\left(1-e^{-k\Delta t}\right)+Pc\left(k\Delta t-1+e^{-k\Delta t}\right)}{k} \tag{12}$$

$$Q_{2,new} = Q_2 e^{-k\Delta t} + Q(1-c)\left(1-e^{-k\Delta t}\right) + \frac{P(1-c)\left(k\Delta t-1+e^{-k\Delta t}\right)}{k} \tag{13}$$

Where,

$Q_{1,new}$: the available energy at the end of the time step (kWh)

$Q_{2,new}$: the bound energy at the end of the time step (kWh)

P: the actual power charged into (negative) or discharged out of (positive) of the battery (kWh)

A new generic component for Li-Ion battery has been created in HOMER’s library for this research. Table 5 lists the key technical parameters of this battery module. All parameter values are replicated from the component named “Generic 1kWh Li-Ion [ASM]”, which is available in HOMER’s component library and uses the advanced kinetic model.

Table 5: Technical parameters and their values for battery storage

Parameter	Value
Nominal voltage (V)	3.7
Maximum capacity, Q_{max} (Ah)	282.7
Capacity ratio, c	0.1207
Conductance, k (1/hr)	159.3
Roundtrip efficiency (%)	92
Maximum charge current (A)	270
Maximum discharge current (A)	810
Minimum state of charge (%)	20

The lifetime of Li-Ion battery needs to be calculated to determine the times of battery replacement over the project life. HOMER calculates battery lifetime based on a predefined number of years (i.e., the float life), or a predefined quantity of energy throughput, or whichever of the above two items happen first. The last option is selected to use in this work. The parameter values of float life and energy throughput are provided in Table 6. Both values are replicated from the component named “Generic 1kWh Li-Ion [ASM]”, which is available in HOMER’s component library. For informational purposes, the data points (i.e., the depth of discharge and the corresponding number of cycles to failure) of battery life tests used to derive the energy throughput are provided in APPENDIX: C.

Table 6: Technical input parameters for battery storage modules

Parameter	Value	Source
Float life (yrs.)	15	HOMER 2022
Throughput (kWh)	2,742	HOMER 2022
O&M ($/kWh-yr.)	10	Mongird *et. al.* 2020

Compared with PV system installed prices, there are much less resources on the cost of battery energy systems. Table 7 shows the battery module costs where similarly, to the PV price model shown earlier the battery price model was constructed using a recent study done by LBNL (Barbose *et. al.* 2022) as well as an upper bound value from an NREL (Ramasamy *et al.* 2022) study which depicts the national average cost of battery systems in $/kWh based off the total system size. The O&M cost is estimated at $10/kWh-yr. (Mongird et al. 2020). Note that the number of battery modules will be an optimization variable.

Table 7: Battery Model Price Blocks

Source	System Size (kWh)	Capital Cost ($/kWh) National Average
LBNL	< 30	1,265
LBNL	30-100	1,061
LBNL	> 100	817
NREL	1200	610

3.5.3 Power Converters

Relative to other components, the power converter has much simpler inputs. For the grid-tied PV inverter, efficiency and DC/AC load ratio are the two major technical parameters while for other inverters, efficiency is the only technical parameter to be specified. The DC/AC load ratio is specified as 1.2, which is consistent with the surveyed data (Barbose et al. 2022). The efficiency of power converters (including both inverters and the solar charge controller) is set at 96% (Ramasamy *et. al.* 2022). Regarding the economical parameters, the lifetime is set to match the project lifetime of 25 years and the costs, including capital, replacement and O&M do not need to explicitly be considered because converters are included in the PV or battery storage system pricings as discussed earlier.

3.5.4 Diesel Genset

Diesel gensets are always used on poultry farms to ensure continuous power supply in the event of grid power outages. However, the genset plays different roles in the two system configurations. For the off-grid configuration, the genset is utilized as a main power generation source in the hybrid system, while for the grid-connected configuration the genset only acts as a standby emergency power source. It is a convention to size the genset large enough to meet the entire farm load. For the considered poultry farm, the genset has its rated capacity of 100 kW and this size is fixed for both off-grid and grid-connected hybrid systems.

HOMER uses a fuel curve to linearly correlate the power generation and fuel (diesel in this work) consumption. The fuel curve has the following equation (HOMER 2022):

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{14}$$

Where,

F: diesel consumption (L/kWh)

F_0: the fuel curve intercept (L/kWh)

F_1: the fuel curve slope (L/kWh)

Y_{gen}: the rated capacity of the genset (kW)

P_{gen}: the electrical output of the genset (kW)

Default values of the 100-kW diesel generator are used for the fuel curve coefficients, which have $F_0 = 2.8$ and $F_1 = 0.253$ which are derived by HOMER software. Diesel generators have the highest efficiency when they operate at or near full load conditions. At very low load conditions, the engine not only has poor efficiency but can also cause the problem of building up unburned fuel in the engine's exhaust system. Therefore, it is necessary to specify an acceptable minimum load ratio, for which diesel engine manufacturers normally recommend a value no less than 30% (Jabeck 2013). In addition, to extend the life expectancy of the genset, short cycling should be avoided. Therefore, a minimum runtime of 15 minutes is specified according to manufacturer-recommended best operation practices. Table 8 summarizes the technical parameter settings for the diesel genset used in this work.

Table 8: Technical parameters and their values for the diesel generator

Parameter	Value	Source
Rated capacity (kW)	100	Farm owner
Fuel curve intercept, F_0 (L/kWh)	2.8	HOMER 2022
Fuel curve slope, F_1 (L/kWh)	0.253	HOMER 2022
Minimum load ratio (%)	30	Jabeck 2013
Minimum runtime (mins)	15	Standard practice

The life expectancy of diesel generators can vary greatly with the size, the usage, and the level of preventive maintenance services. The React Power Team (2020) states that typically well-maintained gensets can last at least 15,000 hours up to a maximum of 50,000 hours before servicing is needed. For the purposes of this study, the average value of 32,500 hours is used for the lifetime of the generator. Considering that the diesel genset already exists in the current farm, its capital cost is set at zero. However, the replacement cost is fully considered in the off-grid configuration because the regular and intensive use of the diesel genset will likely incur replacement during the project life period, which is not the case of emergency use in current farm operations. The O&M cost is estimated at $0.02 per kW per operating hour (Schenkman, 2020). The diesel price has fluctuated significantly in the past 15 years, as shown in Figure 9 that presents the historical retail prices of ultra-low-sulfur diesel in the East Coast from 2007 to 2022 (EIA 2022). Even with the significant fluctuations, the average prices over the last 15 years, the last 10 years and the last 5 years are very close. The average value of $0.86/L over the last 5 years is used in this work (EIA 2022). Table 9 summarizes the economic parameter values for the diesel genset.

Figure 9: Diesel Fuel Price Variability Since 2007 (EIA 2022)

Table 9: Parameters and inputs for diesel generator

Parameter	Value	Source
Lifetime (operating hrs.)	32,500	React Power Team 2020
Capital cost ($)	0	
Replacement cost ($/kW)	400	
O&M ($/kW/hr.)	0.02	Schenkman, 2020
Fuel Price ($/L)	0.86	EIA 2022

3.5.5 Power Grid

HOMER models the grid mainly to quantify the cost of purchasing power from the grid and the revenue from selling power to the grid. For this purpose, HOMER can define up to 16 different rate schedules that may vary with each other with respect to the energy charge rate, demand rate, and sellback rate. The rate schedules can be applied to different months, days (e.g., weekday and weekend), and time of the day (e.g., peak hours and off-peak hours).

Three different rate structures are defined for the grid-connected configuration. The first two rate structures are respectively based on the rate schedule GS27 (Single-Phase Commercial and Three-Phase Service) and the rate schedule GS27TOU (Single-Phase Commercial and Three-Phase Time-Of-Use) with the Renewable Purchased Power (RPP) Rider, offered by the Randolph Electric Membership Corporation (REMC), an electric cooperative in Asheboro, NC. Note that the RPP Rider is essentially the buy all & sell all compensation mechanism described in Chapter 2.4. The third-rate structure is based on the Medium General Service (MDS) Schedule with the Net Metering Rider, offered by Energy United, an electric cooperative in Statesville, NC. The key information of these three rate structures is summarized in Table 10.

Table 10: Utility energy rates considered

Electric Co-op	Rate Schedule	Energy Charge Rate	Demand Rate	Renewable Rider
Randolph Electric Membership Corporation	GS27	First 200 kWh per kW of billing demand: 8.18 ¢/kWh Next 200 kWh per kW of billing demand: 7.77 ¢/kWh All over 400 kWh per kW of billing demand: 6.6 ¢/kWh	$6.59/kW	Renewable purchased power Selling price at 3.89 ¢/kWh
	GS27TOU	On peak: 9.12 ¢/kWh Off peak: 4.73 ¢/kWh	On peak: $15.78/kW Off peak: $5/kW	Renewable purchased power Selling price at 3.89 ¢/kWh
Energy United	Medium General Service (MGS)	0-3,000 kWh: 5.21 ¢/kWh 3001-30,000 kWh: 4.69 ¢/kWh 30001 and over: 4.22 ¢/kWh	$6.25/kW	Net metering Selling price at 4.23 ¢/kWh

The three rate schedules in Table 10 are selected for the following reasons:

- These rates are representative ones offered by electric co-ops in NC, the type of utility companies that serve most poultry farms.
- These rates have different features, including time of use rates and rates that do not change with time.
- Generally, net metering and buy all & sell all are the two most widely used compensation mechanisms for grid-connected, behind-the-meter distributed generation systems. Even though net metering is not used as much by electric co-ops, it is included here because it is still prevalent in many service territories of investor-owned utilities.

HOMER Pro does not support block rates. Therefore, the energy block rates GS27 of REMC and MGS of Energy United are simplified to flat rates that have the same energy costs based on the load profile in Section 3.3. The flat rates are calculated to be 8.05¢/kWh and 4.7 ¢/kWh, corresponding respectively to GS27 of REMC and MGS of Energy United.

3.5.6 Controller

The controller component specifies how the hybrid system operates during the simulation. At each time step, HOMER determines whether the renewable power is sufficient to meet the electric load and the required operating reserve (for the off-grid system). If not, the dispatchable power sources in the system, such as the diesel genset, the battery, and the grid, must be dispatched to serve the load and the operating reserve. Which dispatchable components are used is based on the principle of cost minimization. The cost of producing energy with each dispatchable component includes two parts: a fixed cost in $/hr. and a marginal cost of energy generation

$/kWh. More details about the fixed cost and marginal cost of HOMER components can be found in (HOMER Energy 2023).

For systems comprising of both battery and diesel generator, the controller needs to determine whether the generator should charge the battery. In this aspect, the following dispatch control strategies are considered in this work:

- Load following: When the generator is dispatched, it produces only enough power to meet the demand, subjective to the generator's constraint on the minimum load ratio.
- Cycle charging: When the generator is dispatched, it operates at full capacity and the surplus power is used to charge the battery, subjective to the battery charging limit.
- Predictive control: The electrical load and the solar resource availability in the next 48 hours are used to minimize the system operating cost. The predictive control strategy is only available for off-grid systems.

CHAPTER 4: SIMULATION RESULTS & ANALYSIS

The purpose of this chapter is to showcase the defined models with all listed inputs and considerations. Simulations are conducted using HOMER Pro to find optimized results for each model and compare the benefits or drawbacks of addition of PV systems using net present cost as the primary object function. The cases to be simulated include all grid connected models and the off-grid hybrid system model, all of which are run for optimized results based on the model input parameter values stated in Chapter 3. Sensitivity analyses are also conducted to investigate the impact of key parameters on the results.

4.1 Simulation Cases

Table 11 lists the HOMER models created and simulated in this work. These models represent 8 different cases based on whether the farm is grid connected, the reference utility company, the rate structure, and the compensation mechanism for onsite power generation.

Table 11: Simulation case models

Case	Case name	Grid connection	Reference utility	Rate structure	Compensation mechanism
1	GC_EU_Block_NM	connected	EnergyUnited	block	net metering
2	GC_REMC_Block_BASA	connected	REMC	block	buy all & sell all
3	GC_REMC_Block_NB	connected	REMC	block	net billing
4	GC_REMC_Block_NM	connected	REMC	block	net metering
5	GC_REMC_TOU_BASA	connected	REMC	time of use	buy all & sell all
6	GC_REMC_TOU_NB	connected	REMC	time of use	net billing
7	GC_REMC_TOU_NM	connected	REMC	time of use	net metering
8	Off Grid Hybrid System	not connected	NA	NA	NA

In Table 11, the first case is based on the Medium General Service (MGS) schedule of EnergyUnited, an electric cooperative headquartered in Statesville, NC. The MGS schedule has a flat demand charge rate and a block rate structure for energy charges (Table 10). EnergyUnited has a pilot net metering rider for non-residential customers. This rider allows the installation of behind-the-meter renewable generation with the rated power not exceeding the lesser of the customer's estimated maximum annual power demand or 150 kW. The rider offers two options with one option (Option A) having a standby charge and the other not (Option B). Option B is used in this work, and it specifies the price of power selling back to be 4.233 cents/kWh.

Cases 2-7 are based on the commercial rate schedules of Randolph Electric Membership Cooperative (REMC) in NC. REMC has a schedule (GS27) with a block rate structure for energy charges and another schedule (GS27TOU) with a time-of-use rate structure. Both schedules are studied in this work and their rate structures are presented in Table 9. REMC has a renewable purchased power rider that requires all onsite power generation to be sold back to the grid. This rider is essentially the buy-all and sell-all (BASA) compensation mechanism for onsite power generation. For cases with the BASA mechanism, the onsite power generation can be investigated simply standalone without the interaction between the PV and the load and therefore, the HOMER model is not needed. To increase the value of this research, net billing and net metering scenarios are added to investigate the impact of compensation mechanisms on the system design and economics even though the two compensation mechanisms are not currently used by REMC.

The last case (Case 8) in Table 11 represents the scenario that the poultry farm is not connected to the power grid. The PV-diesel-battery hybrid system can form a standalone microgrid to meet the electric loads.

Each case that is simulated in HOMER has several optimization variables defined. These variables are left to the HOMER software to optimize for the optimal values based on the net present cost. This is the main purpose of using the HOMER software for this study.

Table 12 lists the optimization variables defined for all HOMER simulation cases. Note that the two cases with buy-all and sell-all do not need HOMER simulation and therefore the optimization variables are not defined. This table shows the following:

- For all grid-connected cases, the PV size is bounded in between 10 kW DC and 109 kW DC. The upper bound is set at the annual peak demand and the lower bound is set to be a small but meaningful value for practical installation.
- The battery size is optimized as the number of strings. Each battery module has a nominal capacity of 1 kWh. The string size is set to 1 and no upper bound is defined for the number of strings.
- The converter size is defined as a non-negative continuous variable to be optimized.
- The dispatch strategy is defined as a discrete variable to be optimized. For all grid-connected cases, the dispatch strategy has two options: load following (LF) and cycle charging (CC). For the off-grid case, an additional predictive dispatch strategy (PS) is used. The predictive strategy is used only in the off-grid case because it is not supported in HOMER for grid-connected systems. All three dispatch strategies are explained in Chapter 3.
- The demand limit is defined as a discrete variable to be optimized for all grid-connected cases. The demand limit indicates the maximum power that can be purchased from the grid. It is used in this work to investigate the effect of demand charges. The three values 80 kW, 90 kW and 100 kW are below the annual peak (109 kW) of the load profile and the value 999 kW simply means no demand limit.

Table 12: Optimization variables for each simulation case model

Cases	Variables				
	PV size (kW DC)	Battery size (# of strings)	Converter (kW)	Dispatch strategy	Demand limit (kW)
GridConnected_EU_Block_NM	[10, 109]	[0, ∞)	[0, ∞)	(LF, CC)	(80, 90, 100, 999)
GridConnected_REMC_Block_BASA	NA				
GridConnected_REMC_Block_NB	[10, 109]	[0, ∞)	[0, ∞)	(LF, CC)	(80, 90, 100, 999)
GridConnected_REMC_Block_NM	[10, 109]	[0, ∞)	[0, ∞)	(LF, CC)	(80, 90, 100, 999)
GridConnected_REMC_TOU_BASA	NA				
GridConnected_REMC_TOU_NB	[10, 109]	[0, ∞)	[0, ∞)	(LF, CC)	(80, 90, 100, 999)
GridConnected_REMC_TOU_NM	[10, 109]	[0, ∞)	[0, ∞)	(LF, CC)	(80, 90, 100, 999)
Off Grid Hybrid System	[0, ∞)	[0, ∞)	[0, ∞)	(LF, CC, PS)	NA

4.2 Simulation results for grid-connected cases

4.2.1 Results for EnergyUnited

Table 13 displays the simulated results for the first grid connected case, the Energy United (Case "GridConnected_EU_Block_NM"). In this table, the base case represents the current situation without the use of PV. The HOMER optimization leads to the following 1) the PV is sized to be 11.3 kW, which is close to the lower bound of 10 kW; 2) no battery and converter are needed; 3) cycle charging is the preferred dispatch control strategy; and 4) the grid power demand is not limited to a value below the annual peak load. The net present cost (NPC) of the optimal solution is higher than the base case of no PV, which does not support PV installation at the poultry farm. Even with net metering, the mechanism that is very favorable for distributed solar development, solar PV is a tough sale at present because the electricity price is low at EnergyUnited.

Table 13: GridConnected_EU_Block_NM Case Results

Case	PV (kW)	Battery (kWh)	Converter (kW)	Dispatch strategy	Demand limit (kW)	Net present cost ($)
No PV (base)	NA					227,332
GridConnected_EU_Block_NM	11.3	0	0	CC	999	238,622

It is worthwhile to verify the optimal solution obtained by HOMER. Therefore, a HOMER model has been created to have six PV sizes (i.e., 10 kW, 11 kW, 12 kW, 13 kW, 14 kW, and 15 kW) while keeping all other variable definitions unchanged. After optimization, the NPC results corresponding to the above five PV sizes are $239047, $237367, $238311, $239256, $240200,

$241145, respectively. The optimal PV size lies in between 11 kW and 12 kW and this verifies the optimal PV sizing of 11.3 kW.

4.2.2 Results for REMC with block rates

Table 14 summarizes the results of the cases based on the REMC block rate structure. The base case represents the current situation without PV. The case of buy-all and sell-all (GridConnected_REMC_Block_BASA) is based on manual calculation while the net billing (NB) case (GridConnected_REMC_Block_NB) and the net metering (NM) case (GridConnected_REMC_Block_NM) are obtained from HOMER simulation. Table 14 shows the following:

- For buy-all and sell-all, which is the existing rider for distributed solar PV installation, the revenue of selling the PV power generation is not sufficient to recover the capital cost and the O&M cost. The net present cost increases with the PV size. Therefore, the smallest PV size (i.e., 10 kW) is used and it has the lowest NPC of $360497.
- If the compensation mechanism is changed from buy-all and sell-all to net billing, the optimal solution has the PV size of 20 kW, no use of battery and converter, the cycle charging dispatch strategy and no stringer power demand limit. Because the NPC of using 20-kW PV is higher than that of the base case, solar PV investment is not profitable.
- If the compensation mechanism is changed from buy-all and sell-all to net metering, the optimal solution has the PV size of 101 kW, no use of battery and converter, the cycle charging dispatch strategy and no stringer power demand limit. Because the NPC of using 101-kW PV is lower than that of the base case, solar PV investment is profitable. However,

the simple payback period is calculated to be ~12 years, which is too long to be considered as an attractive investment.

Table 14: REMC block rate case results

Case	PV (kW)	Battery (kWh)	Converter (kW)	Dispatch strategy	Demand limit (kW)	Net present cost ($)
REMC No PV (base)	NA					346,545
GridConnected_REMC_Block_BASA	10	NA				360,497
GridConnected_REMC_Block_NB	20.3	0	0	CC	999	349,769
GridConnected_REMC_Block_NM	101	0	0	CC	999	341,851

The optimal PV sizes obtained by HOMER are verified in a similar manner as the approach used for the EnergyUnited case. For the net metering case, for example, a HOMER model has been created to have five PV sizes (i.e., 99 kW, 100 kW, 101 kW, 102 kW, and 103 kW) while keeping all other variable definitions unchanged. After optimization, the NPC results corresponding to the above five PV sizes are $362523, $341809, $341884, $341959, and $342035, respectively. The optimal PV size lies in between 100 kW and 101 kW, and this basically verifies the optimal PV sizing of 101 kW.

Figure 10 shows the components that contribute to the net present cost for different cases. The residual value of the diesel generator is the same for all cases and it takes a negative value because the net present cost is considered. For the cases of net billing and buy-all & sell-all, the power purchase cost dominates the NPC (>90%) because the PV size is small. Even for the net metering case with 101 kW PV, the power purchase cost contributes to 62% of the NPC.

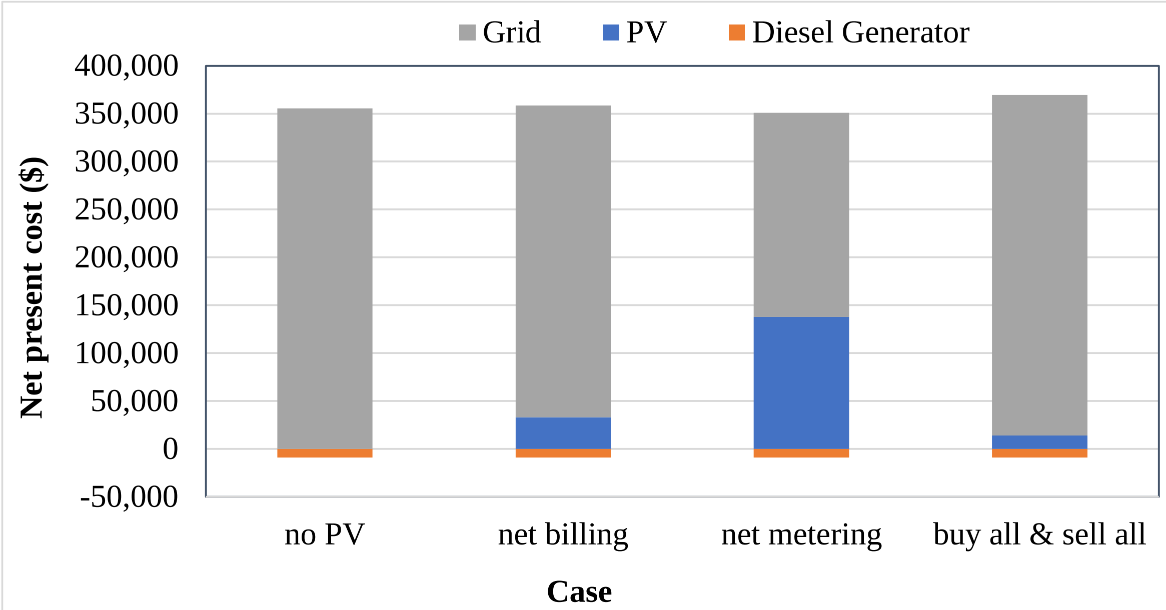

Figure 10: NPC comparison for all REMC block rate case results.

4.2.3 Results for REMC with TOU rates

Table 15 summarizes the results of the cases based on the REMC time of use (TOU) rate structure. The base case represents the current situation without PV. The case of buy-all and sell-all (GridConnected_REMC_TOU_BASA) is based on manual calculation while the net billing and net metering cases (GridConnected_REMC_TOU_NB) and (GridConnected_REMC_TOU_NM) are obtained from HOMER simulation. Table 15 shows the following:

- For buy-all and sell-all, which is the existing rider for distributed solar PV installation, the revenue of selling the PV power generation is not sufficient to recover the capital cost and the O&M cost. The net present cost increases with the PV size. Therefore, the smallest PV size (i.e., 10 kW) is used and it has the lowest NPC of $427315.
- If the compensation mechanism is changed from buy-all and sell-all to net billing or net metering, the optimization variables take the following values: a 11-kW PV, no use of battery and converter, the cycle charging dispatch strategy and no stringer power demand

limit. For both net metering and net billing, the solar PV investment is not profitable because they have a higher NPC than the base case.

Table 15: REMC time of use case results

Case	PV (kW)	Battery (kWh)	Converter (kW)	Dispatch strategy	Demand limit (kW)	Net present cost ($)
REMC TOU, No PV (base)	NA					413,363
GC_REMC_TOU_BASA	10	NA				427,315
GC_REMC_TOU_NB	11	0	0	CC	999	418,985
GC_REMC_TOU_NM	11	0	0	CC	999	418,821

Relative to the block rate structure, the TOU rate structure leads to a higher NPC for all cases. While PV investment is profitable for net metering under the block rate structure, it is not profitable under the TOU rate structure. In this case, the REMC TOU rate structure is less favorable for poultry solar development than the REMC block rate structure.

4.3 Results for the Off-Grid hybrid system

Table 16 shows the HOMER optimization results for the off-grid hybrid system. The optimal component sizing includes a 250-kW PV array, a 396-kWh battery pack, and a 163-kW converter. The predictive dispatch is selected to be the optimal control strategy. The system has an NPC of $783045, which is significantly higher than all grid-connected systems presented so far.

Table 16: Off-Grid System Optimization Results

Variables				**Net Present Cost ($)**
PV (kW)	**Battery (kWh)**	**Converter (kW)**	**Dispatch Strategy**	
250	396	163	PS	783,045

To verify the optimization results, a HOMER model is created to have the following search spaces: 5 PV sizes (248 kW to 252 kw with a step of 1 kW), 5 battery sizes (394 kWh to 398 kWh with a step of 1 kWh), and 5 converter sizes (161 kW to 165 kW with a step of 1 kW). The predictive dispatch strategy is used in this model. After optimization, the combination of 250-kW PV, 394-kWh battery and 161-kW converter has the lowest NPC of $782722. The difference between $782722 and $783045 is only $323. Considering the huge search space of the original optimization problem, the performance of the HOMER optimization engine is really reliable.

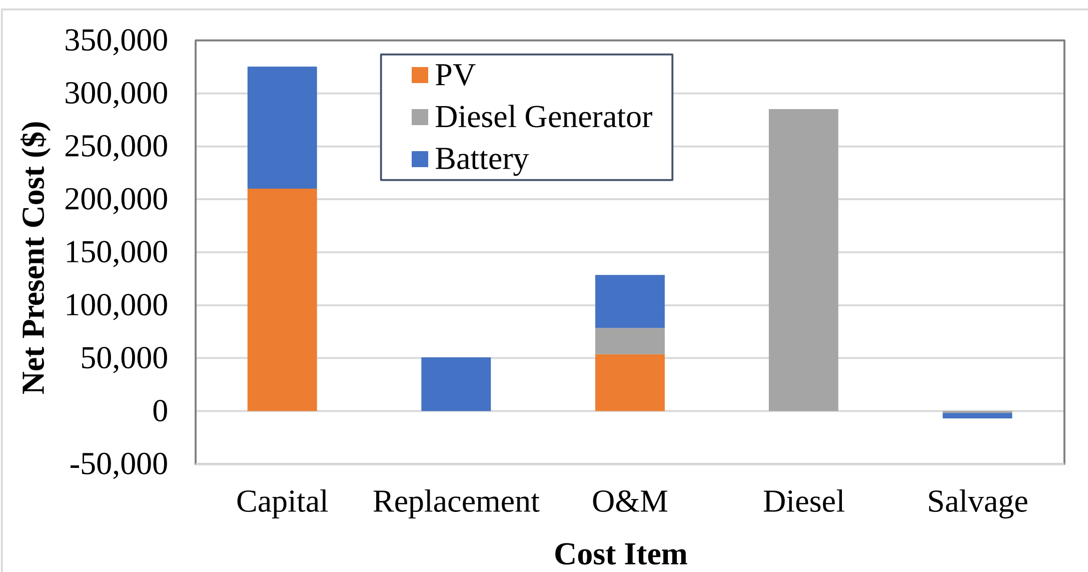

Figure 11: Off-grid system net present cost summary

The cost summary showing net present costs of the system in Figure 11 shows the net present cost due to capital investment, replacement, operation and maintenance (O&M), diesel consumption, and salvage values. All these cost items are from the PV array, diesel generator, and battery. The costs of the converter and the controller are included in the battery management system. Figure 11 indicates the following:

- Among all cost items, the capital cost is the largest, contributing 42% of the off-grid hybrid system NPC. The capital cost includes PV and battery. Because a 100-kW diesel generator is used across all grid-connected systems and the off-grid system, its capital cost is not considered and thus not shown in FIGURE 16. The PV array and the battery package account for 27% and 15% , respectively, of the total NPC of the system.
- The diesel fuel cost is the second largest cost item, contributing 36% of the off-grid hybrid system NPC.
- Battery needs to be replaced once over the project life of 25 years. Further investigation shows that battery replacement occurs on the 14th year.
- The O&M cost is not negligible at all. It contributes about 16% of the system NPC. Most of the O&M cost comes from the PV and battery maintenance.

Figure 12 presents the distribution of the NPC among the three components: PV, battery and diesel generator. It can be seen that the diesel generator accounts for 39% of the NPC because of its fuel cost while the PV and the battery account for 34% and 27% of the NPC, respectively.

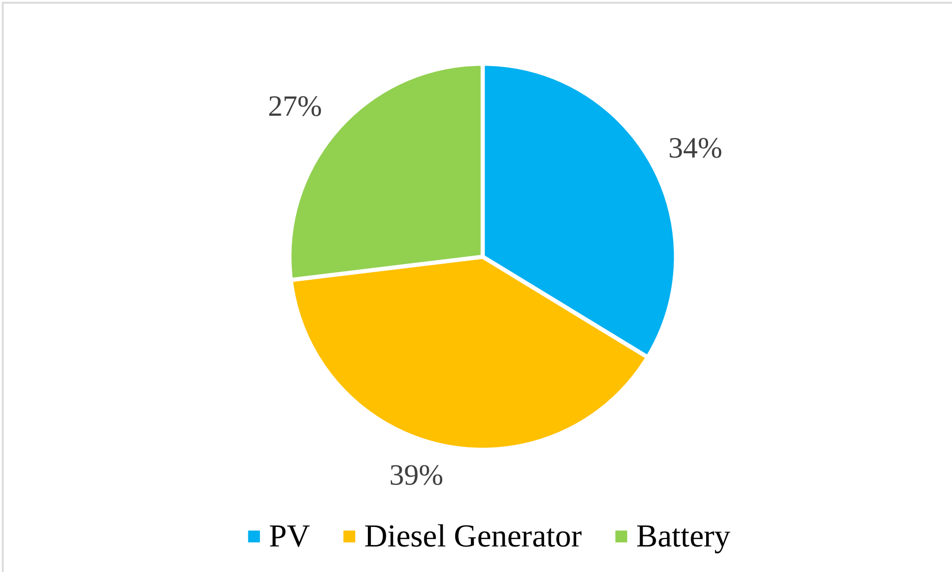

Figure 12: Hybrid system distribution of NPC per component

Figure 13 shows the monthly energy consumption and energy production by the PV array and the diesel generator. The diesel generator is used in all months except February and May. The annual energy production is 379 MWh from PV and 93 MWh from the diesel generation. The total annual energy production is far more than the annual energy consumption (264 MWh) of the electric loads. This happens because of the mismatch between energy production and consumption. Even though battery is used for energy storage, there is about 188 MWh excess energy annually. Due to the nature of optimization, lowering the capacity of the PV array in order to reduce excess energy would not lower the systems NPC. This excess energy exists because it is more economically viable to use a larger PV array size for lower initial costs while also ensuring the operating reserve is being kept at all times. In the case of this study an operating reserve of 10% of the load in the current time step must be maintained. The uses for this excess energy could be explored such as using it to power/charge various equipment or utilities on the farm.

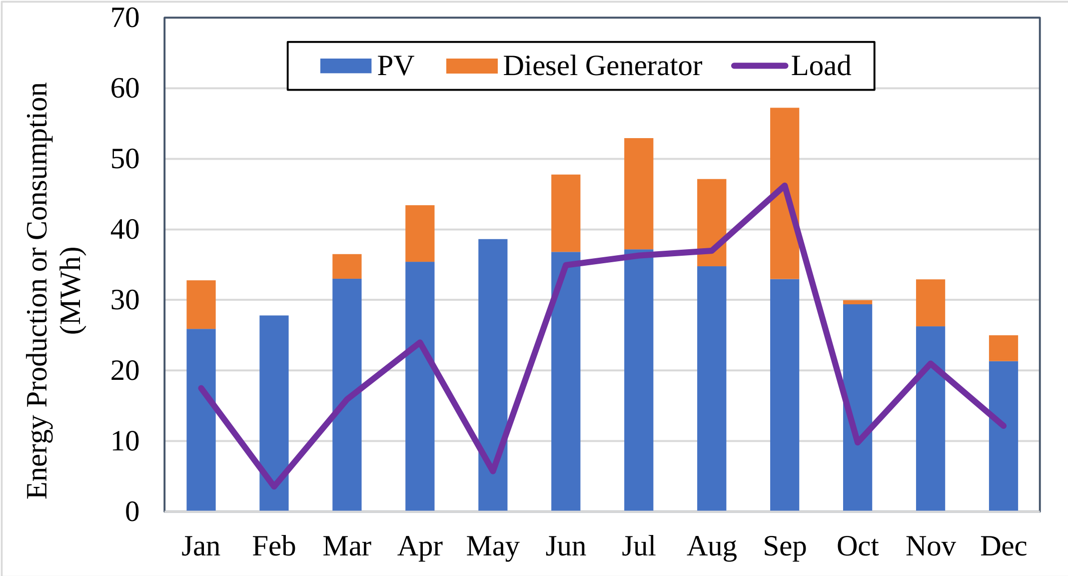

Figure 13: Hybrid system energy production and consumption per month

The levelized cost of electricity (LCOE) of the off-grid hybrid system is calculated to be 0.2342 $/kWh, which is a relatively high generation cost.

The emissions of the off-grid hybrid system are calculated and compared with those from the grid-connected system without the use of PV. The emission factors of the NC power grid are 317 g/kWh for Carbon Dioxide, 0.32 g/kWh for Nitrogen Oxide, and 0.18 g/kWh for Sulfur Dioxide (EIA 2022). The results are presented in Table 17. The off-grid hybrid system has 18% reduction of CO_2, 56% reduction of NO, but about 2.5 times SO_2 more than the grid-connected system with the use of PV.

Table 17: Emissions comparison: Grid-connected vs. off-grid

Emissions	Grid-connected & no PV	Off-grid hybrid
Carbon Dioxide (kg/yr.)	83,699	68,505
Nitrogen Oxide (kg/yr.)	84.5	37.3
Sulfur Dioxide (kg/yr.)	47.5	168

4.4 Sensitivity Analysis

Sensitivity analysis aims to understand how responsive the net present cost of the optimized PV-diesel-battery hybrid system is to the change of certain inputs. As presented in Sections 4.2 and 4.3, the optimal system configurations with PV seldom had lower NPC than the conventional grid-connected systems without the use of PV. Considering that the component prices are dynamic with technology advancement and market conditions, and they are expected to have big impact on the results, the sensitivity analysis has a focus on the price of PV, battery, utility, and diesel fuel. Table 18 lists the perturbations of each sensitivity variable expressed in percentages of their original inputs. In particular, the 75% of the original PV price represents the case if the farmer is awarded the Rural Energy for America Program (REAP) grant offered by the U.S. Department of Agriculture. Unlike the federal tax incentives, the REAP grant is competitive and it provides the amount of grant up to 25% of the renewable energy system investment but no more than $500,000.

Table 18: List of perturbations on sensitivity variables

Sensitivity Variable	**Perturbations**	**System Studied**
PV price	85%, 75%, 60%	Both grid-connected and off-grid systems
Battery price	90%, 80%, 70%	Both grid-connected and off-grid systems
Diesel price	90%, 80%, 70%	Both grid-connected and off-grid systems
Grid power purchase price	90%, 80%, 70%	Grid-connected systems only
Onsite power selling price	110%, 120%, 130%	Grid-connected systems only REMC

In the table above, the perturbations on onsite power selling price are only altered on REMC cases. This is because if the prices were to be changed in EnergyUnited cases the sell price would become higher than the purchase price which would lead to unrealistic results.

4.4.1 Results of sensitivity analysis for EnergyUnited

HOMER is used to run all perturbed cases. With the optimal solutions for all perturbed cases collected the following observations can be made:

- Battery and converter are not used in the optimal solution for all perturbed cases, which is the same as the case before perturbation.
- Cycle charging is the preferred dispatch control strategy for all perturbed cases, which is the same as the case before perturbation.
- A stringer power demand limit is not used in the optimal solution for all perturbed cases, which is the same as the case before perturbation.

- The optimal PV size is 11 kW for all perturbed cases except for the one with PV price multiplier of 0.6, which has the optimal PV size of 101 kW.

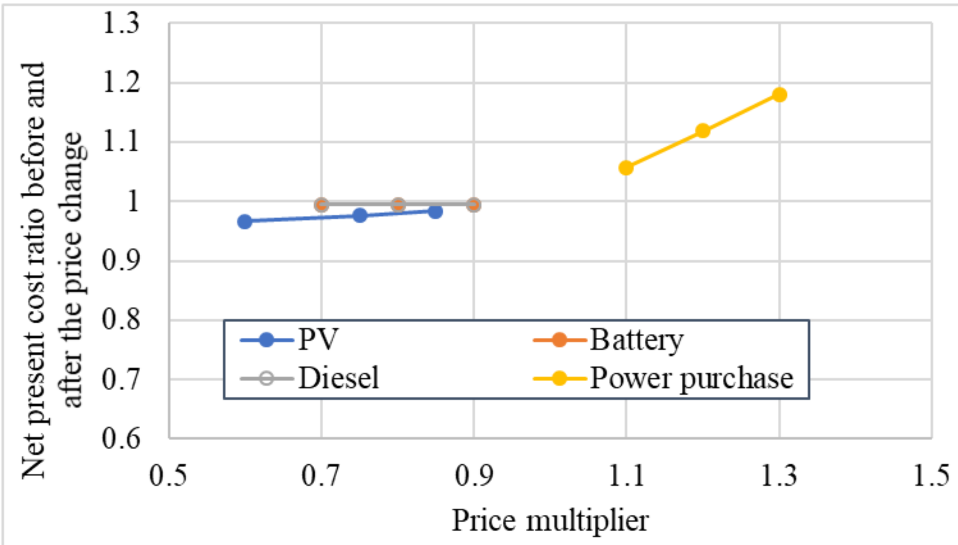

Figure 14: Change in NPC by sensitivity type for EnergyUnited case

Figure 14 shows how the NPC values of all perturbed cases change relative to the original case. In this figure, the vertical axis represents the ratio of the obtained optimal NPC values before and the price change. This figure indicates the following:

- The obtained optimal NPC value does not change even if the battery price or diesel price is reduced by 30%.
- Relative to the original case, the obtained optimal NPC value decreases slightly by 3.3% if the PV price is reduced by 40%. The NPC value corresponding to the case of PV price multiplier being 60% is $230629, which is still higher than the NPC of the case without PV installation ($227332, see Table 13).
- Apparently, increasing the grid power purchase price causes a significant NPC to increase relative to the original case.

4.4.2 Results of sensitivity analysis for REMC with block rates

Table 19 shows the optimal PV sizes of all perturbed cases and the corresponding NPC values. The battery size, converter size, dispatch strategy, and grid power demand limit are the same as the original case and therefore they are not listed in Table 19. By comparing this table with Table 14, one can make the following observations:

- For both net billing and net metering, the optimal PV size and NPC do not change even if the battery price or diesel price is reduced by 30%.
- For net billing, the optimal PV size is the same as the original case if the PV price is reduced by 15%; however, the PV size is increased to 101 kW and 109 kW (the upper bound) respectively if the PV price is reduced by 25% and 40%. Solar investment becomes profitable after the PV price is reduced by 15% or more because the NPC of the perturbed cases is lower than the case of not using PV, which has an NPC of $346545. The simple payback period is calculated to be 12.1 years, 11.3 years, and 9.2 years respectively for the PV price reduction of 15%, 25%, and 40%.
- For net metering, the PV size is increased from 101 kW of the original case to 109 kW (the upper bound) if the PV price is reduced by 15% or more. Because solar investment is already profitable before PV price reduction, reducing the PV price further enhances the profitability. The simple payback period is reduced from 12.2 years for the original case to 7.4 years after the PV price is reduced by 40%.
- For both net billing and net metering, the optimal PV size does not change even if the excess PV power selling price is increased by 30%. Relative to the case not using PV, increasing the selling price by 30% does not make solar investment profitable for net billing and it has negligible impact on the profitability of solar investment for net metering.

- The grid power purchase price affects the NPC of the base case without the use of PV. Therefore, the NPC value of the base case in Table 14 cannot be used for comparison. The new NPC values of the base case using the perturbed grid power purchase prices are calculated to be $373633, $400387, and $427475, respectively for the power price multiplier of 1.1, 1.2, and 1.3. Relative to the new base cases, solar PV becomes profitable for net billing if the grid power purchase price is increased by 20% or more. The optimal PV size is 101 kW for net billing if the grid power purchase price is 30% more than the original value. For net metering, increasing the grid power purchase price further enhances the profitability of solar PV investment. The simple payback period is reduced from 12.2 years for the original case to 9.3 years after the grid purchase price is increased by 30%.

Table 19: Sensitivity results for REMC block rate cases

Perturbed variable	Multiplier	Net Billing		Net Metering	
		PV size (kW)	NPC ($)	PV size (kW)	NPC ($)
PV price	0.85	20.3	345,454	109	323,622
	0.75	101	336,207	109	311,055
	0.6	109	318,307	109	292,206
Battery price	0.9	20.3	349,769	101	341,851
	0.8	20.3	349,769	101	341,851
	0.7	20.3	349,769	101	341,851
Diesel price	0.9	20.3	349,769	101	341,851
	0.8	20.3	349,769	101	341,851
	0.7	20.3	349,769	101	341,851
Onsite power selling price	1.1	20.3	349,595	101	340,987
	1.2	20.3	349,422	101	340,122
	1.3	20.3	349,248	101	339,255
Grid power purchase price	0.9	20.3	374,219	109	355,589
	0.8	20.3	398,367	109	368,544
	0.7	101	420,767	109	381,661

Figures 15 and 16 show how the NPC values of all perturbed cases change relative to the original case (i.e., the case without the use of price multipliers). In these two figures, the vertical axis represents the ratio of the obtained optimal NPC values before and the price change. These figures indicate that within the ranges of considered price multipliers, the NPC is sensitive to the PV price and the grid power purchase price but not to the battery price, the diesel price, and the onsite power selling price.

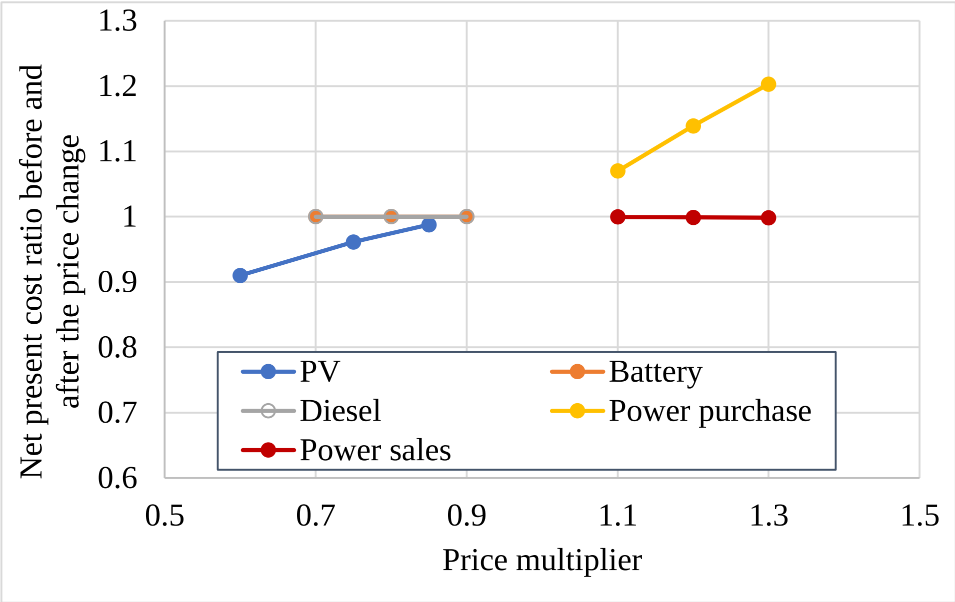

Figure 15: Change in NPC by sensitivity type for REMC_BR net billing case

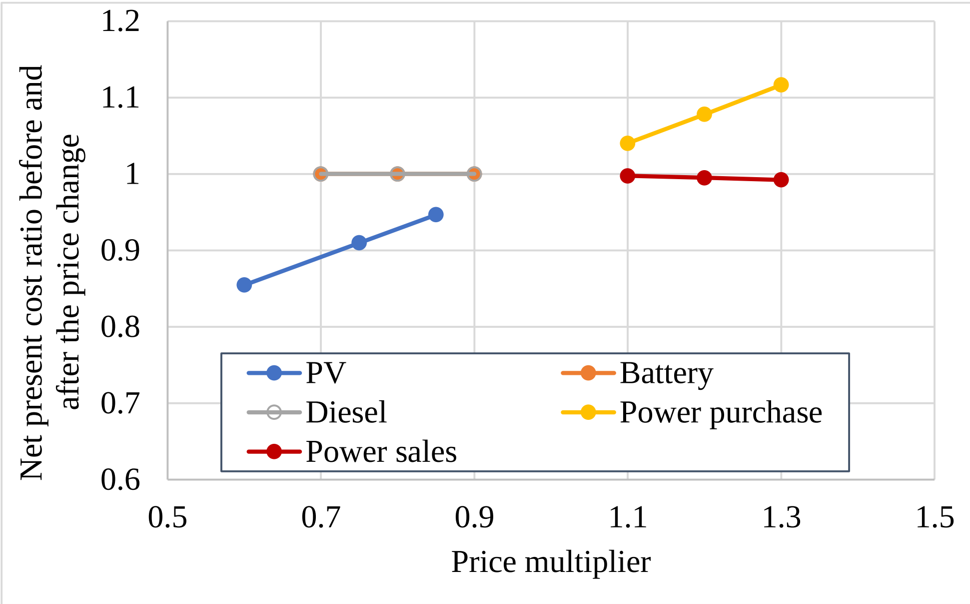

Figure 16: Change in NPC by sensitivity type for REMC_BR net metering case

4.4.3 Results of sensitivity analysis for REMC with TOU rates

Table 20 shows the optimal PV sizes of all perturbed cases and the corresponding NPC values. The findings are similar to the table for REMC with block rates. The battery size, converter size, dispatch strategy, and grid power demand limit are the same as the original case and therefore they are not listed in Table 20. By comparing this table with Table 15, one can make the following observations:

- For both net billing and net metering, the optimal PV size and NPC do not change even if the battery price or diesel price is reduced by 30%.
- For net billing, the optimal PV size takes the same value (i.e., 11 kW) as the original case if the PV price is reduced by 15%; however, the PV size is increased to 20.3 kW and 101 kW respectively if the PV price is reduced by 25% and 40%. Solar investment becomes profitable after the PV price is reduced by 40% because the NPC of the perturbed case is lower than the case of not using PV, which has an NPC of $413363. The simple payback period is calculated to be 11.2 years for the case with PV price reduction of 40%.
- For net metering, the PV size is increased from 11 kW of the original case to 20.3 kW if the PV price is reduced by 15% and 25% and increased to 109 kW (the upper bound) if the PV price is reduced by 40%. Solar investment becomes profitable after the PV price is reduced by 25% or more. The simple payback period is calculated to be 12.4 years if the PV price is reduced by 25% and 10.4 years if the PC price is reduced by 40%.
- For both net billing and net metering, the optimal PV size does not change even if the excess PV power selling price is increased by 30%. Relative to the case not using PV, increasing the selling price by 30% does not make solar investment profitable.

- The grid power purchase price affects the NPC of the base case without the use of PV. Therefore, the NPC value of the original base case in TABLE 15 cannot be used for comparison. The new NPC values of the base case using the perturbed grid power purchase prices are calculated to be $431516, $449948, and $468156, respectively for the power price multiplier of 1.1, 1.2, and 1.3. Relative to the new base cases, solar PV is not a profitable investment for both net billing and net metering.

Table 20: Sensitivity results for REMC time of use cases

Perturbed variable	Multiplier	Net Billing		Net Metering	
		PV size (kW)	NPC ($)	PV size (kW)	NPC ($)
PV price	0.85	11	416,292	20.3	415,840
	0.75	20.3	413,509	20.3	412,963
	0.6	101	404,143	109	397,089
Battery price	0.9	11	418,985	11	418,821
	0.8	11	418,985	11	418,821
	0.7	11	418,985	11	418,821
Diesel price	0.9	11	418,985	11	418,821
	0.8	11	418,985	11	418,821
	0.7	11	418,985	11	418,821
Onsite power selling price	1.1	11	418,932	11	418,821
	1.2	11	418,879	101	418,821
	1.3	11	418,826	101	418,821
Grid power purchase price	0.9	11	436,145	11	435,754
	0.8	11	453,567	20.3	452,597
	0.7	20.3	470,279	20.3	469,250

Figures 17 and 18 show how the NPC values of all perturbed cases change relative to the original case (i.e., the case without the use of price multipliers). In these two figures, the vertical axis represents the ratio of the obtained optimal NPC values before and the price change. These figures indicate that within the ranges of considered price multipliers, the NPC is sensitive to the PV price and the grid power purchase price but not to the battery price, the diesel price, and the onsite power selling price. In comparison with Figures 15 and 16 for block rates, the NPC seems to be less sensitive to the PV price under the TOU rates.

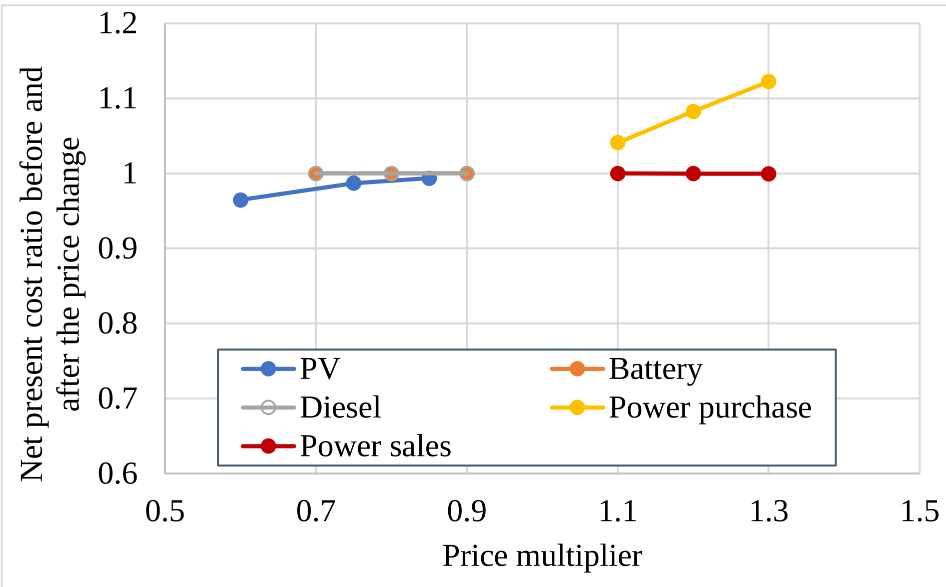

Figure 17: Change in NPC by sensitivity type for REMC_TOU net metering case

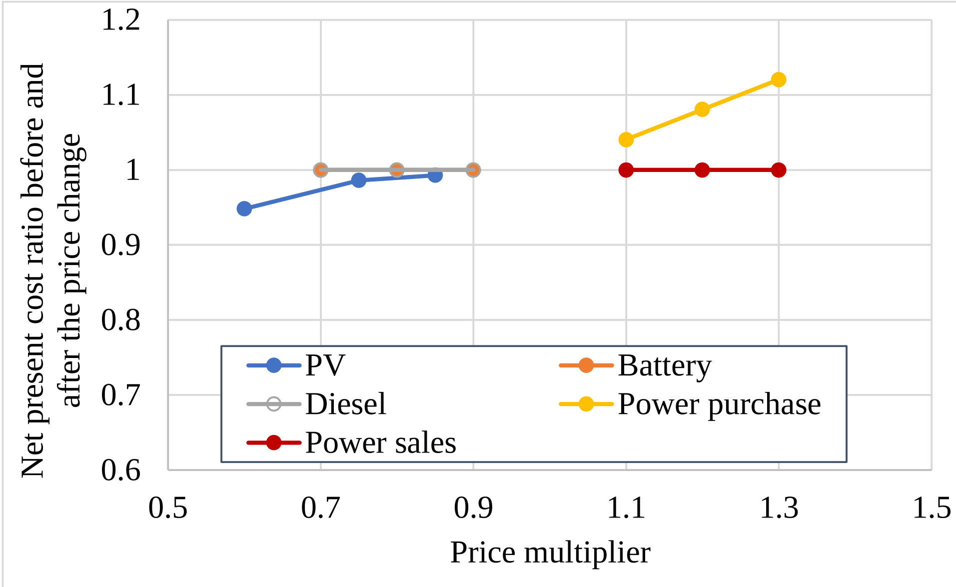

Figure 18: Change in NPC by sensitivity type for REMC_TOU net metering case

4.4.4 Results of sensitivity analysis for the off-grid system

Table 21 lists the optimal variable values and the corresponding NPC for all perturbed cases. This table indicates the following:

- The optimal PV size is 250 kW for most cases, but it is reduced to about 180 kW if the diesel price is reduced by 20% or more.
- There is no clear trend of changes for the battery size and the converter size.
- The predictive dispatch control is always selected for all cases.

Table 21: Sensitivity results for off-grid hybrid system

Perturbed variable	Multiplier	PV (kW)	Battery (kWh)	Converter (kW)	Dispatch Strategy	Net Present Cost ($)
PV price	0.85	251	424	139	PS	752,266
	0.75	250	379	161	PS	730,555
	0.6	250	388	150	PS	698,828
Battery price	0.9	250	402	145	PS	762,339
	0.8	250	402	145	PS	750,771
	0.7	250	432	138	PS	734,229
Diesel price	0.9	250	365	149	PS	754,579
	0.8	182	349	156	PS	723,608
	0.7	180	340	131	PS	687,024

Figure 19 shows how the NPC values of all perturbed cases change relative to the original case (i.e., the case without the use of price multipliers). In this figure, the vertical axis represents the ratio of the obtained optimal NPC values before and the price change. This figure indicates that for the off-grid hybrid system, the diesel price, the PV price, and the battery price has an ascending order of significance with respect to their impact on the NPC.

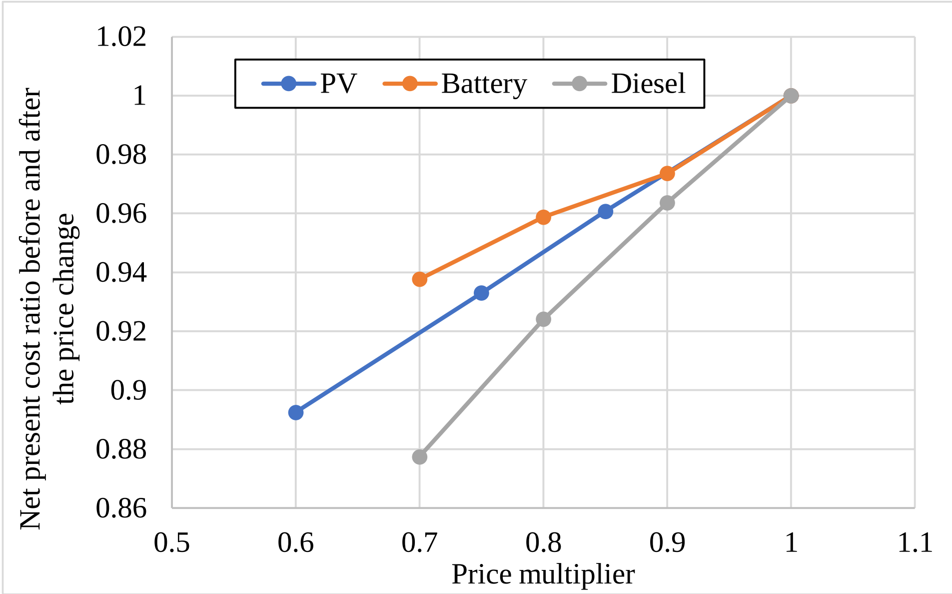

Figure 19: Change in NPC by sensitivity type for hybrid system

4.5.6 Observations from Sensitivity Analysis

From the sensitivity analysis done, there are many observations to make with the large amount of results provided. For the first section when considering PV pricing alone, the overall results show that with systems connected to a retailer that offers low competitive prices for power, the inclusion of a PV array because far less feasible. For a co-op like United Energy, the rates for buying power average out to only 4.8¢ per kWh, with demand rates of 6.25$/kW/mo. For these lower end rates PV price would have to drop by around 40% to be considered as an economic option. For the off-grid model, there is a substantial amount of the NPC that would be saved if PV price were to fall. Although the price of fuel in the system is the biggest cost component, having the price of PV drop by 30% could cut off $65,000 of the systems NPC.

For other co-ops things can differ, for instance with Randolph Electric Membership Corporation (REMC) they offer different rate types for different services. For on and off-peak time service their rates average out to roughly 5.5-6¢ per kWh, while their block rate style service averages out to 8¢ per kWh. Both rates are useful under different load needs, but both would require a PV price drop of 15-30% to become feasible for PV inclusion.

As for the battery price, as explained before, the capital and replacement costs involved with this technology is a considerable portion of the NPC in the off-grid system, however, without the change of diesel price or PV price it is not substantial enough to impact the NPC to a large degree. The results obtained showed that if prices were to drop by 30% then a deduction of $50,000 from the NPC is all that could be expected. Utility price showed that, as stated previously in the PV price analysis, the rates would have to increase substantially in order to make a PV option feasible. The price of power would need to reach over 0.08$/kWh with an increase in sellback price in order to see a PV included system become viable economically. For the diesel price, as anticipated the cost savings were marginally better than other components when fuel prices dropped. With just a 20% drop $60,000 fell off the NPC and a 30% drop increased that amount to almost $100,000.

CHAPTER 5: Conclusions and Future Work

Poultry farms require a significant amount of energy to maintain the appropriate living conditions for chickens. The energy used in poultry farms is mainly for poultry house heating and cooling, ventilation, lighting, feed lines, manure management, and the operation of farm machinery. For many poultry growers, energy cost is their second highest expense, right behind the house mortgages. Cutting utility bills via renewable energy generation on site is important to increase the profitability of poultry growers. There is increasing interest in deploying solar PV in poultry farms. In this work, HOMER Pro microgrid software was used to simulate and optimize the PV-diesel-battery hybrid system for poultry farms. The electric load profile was based on the actual metered power with 15-minute intervals for a poultry farm in NC. Typical meteorological year data were used for solar radiation and ambient air temperature. Generic configuration was defined separately for grid-connected systems and off-grid systems. Major component sizes were then optimized using HOMER for different cases that vary with the utility rate structure and solar power compensation mechanisms. HOMER software was also used to perform the sensitivity analysis with component prices as the perturbed variables. Based on the HOMER simulation results, the following conclusions can be made:

- Solar PV investment was found to be profitable when given the correct circumstances. The first case being utility rate structure, even though the plans offered by EnergyUnited included net metering capabilities, the purchase price of power was low enough to beat out the high initial costs of solar investment. REMC rates showed that the power purchase prices they offered were high enough to encourage the use of PV if PV price were to drop/be reduced by 20-30%, or the same purchase price was offered but with net metering options available.

- The use of battery was found to not be cost effective in grid connected systems because the initial cost of battery is still high at present.
- The optimal size for the off-grid PV-diesel-battery hybrid system consisted of a 250-kW PV array, a 394-kWh battery system, and a 161-kW converter along with the 100-kW diesel generator, which yielded an NPC of $782722. The off-grid hybrid system had a much higher NPC ($370,000 to $560,000) than the grid-connected systems.
- It was seen from the results that the diesel fuel price had a large effect on the system NPC, however, with current prices having more renewable generation and a larger storage system would lead to an overall higher NPC even with less generator operation. Under the current architecture for the system, the change in diesel fuel price had the largest impact on NPC.

Since the renewable technologies advance quickly, it is worthwhile to consider the following future work:

- Currently, the two most prominent battery technologies are lead-acid and lithium-ion. Lithium-ion batteries were used in this work, however, there are other battery technologies such as flow batteries that could be promising in poultry farm applications. Future work may consider the use of other battery technologies.
- The control strategies available in HOMER were used in this work (load following, cycle charging, and predictive). They are acceptable for system design based on a predefined load profile and weather conditions. However, these predefined profiles rarely hold in real system operation. It is important to use model predictive control based on the forecasts of load and weather conditions. In this respect, it is worthwhile to consider implementing the model predictive control in MATLAB, which is then coupled with HOMER.

- The current work considered electricity only. Poultry farms also need energy for heating. Future research could be performed to use excess electricity or diesel generator heat recovery for poultry house heating, which could potentially improve the economics of PV-diesel-battery hybrid systems.

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APPENDIX A: LIST OF USER INPUTS

Category	Input Identifier	Input Value	Reference
Electric Load			
	Eletric Load	User Import	Jonas Asbill Poultry Farm Energy Usage Data (15-min Intervals)
Resources			
	Solar GHI	User Import	https://nsrdb.nrel.gov/data-viewer
	Temperature	User Import	https://nsrdb.nrel.gov/data-viewer
Economics			
	Nominal Discount Rate (%)	8.75	Ramasamy et. al. 2022
	Expected Inflation Rate (%)	2.5	Ramasamy et. al. 2022
	Project Lifetime (yr)	25	
Constraints			
	Operating Reserve		
	Percentage of Load (%)	10	https://www.homerenergy.com/products/pro/docs/3.14/_constraints.html
	Solar Power Output (%)	80	https://www.homerenergy.com/products/pro/docs/3.14/_constraints.html
Optimization			
	Mins per Time Step (mins)	15	*As per Electric Load Data
Controller			
	Grid Connected	CC, LF	
	Off-Grid	CC, LF, & Predictive	
Diesel Genset			
	Rated Capacity (kW)	100	Farm Default Size
	Capital Cost ($)	0	Considered in Farm Costs
	Replacement Cost ($/kW)	400	
	Minimum Load Ratio (%)	30	Jabeck 2013
	Lifetime (op. hrs.)	32500	React Power Team 2020
	Minimum Runtime (mins)	15	Standard Value
	Electrical Bus	AC	*
	O&M ($/op.hr.)	0.02	Schenkman, 2020
	Fuel Price ($/L)	0.86	EIA (energy information association)
PV Module			
	Rated Capacity (kW)	1	*
	Capital Cost ($/W)	(See PV Cost)	Ramasamy et. al. 2022
	O&M ($/kW/yr.)	17	Walker et. al. 2020
	Lifetime (yrs.)	25	Ramasamy et. al. 2022
	Derating Factor (%)	86	NREL – PVWatts Loss Calculator
	Electrical Bus	DC/AC	**
	Ground Reflectance (%)	20	HOMER Glossary
	Panel Azimuth (° S)	0	HOMER Glossary
	Panel Slope (°)	20	NREL – PVWatts Calculator
	Temp Effect on Power (%/°C)	-0.45	Sun et. al. 2021
	NOCT (°C)	45	Sun et. al. 2021
	Efficiency at STC (%)	20.3	Ramasamy et. al. 2022
	PV Inverter Ratio(Grid Only)	1.2	Ramasamy et. al. 2022

Li-Ion Battery			
	Battery Chemistry	Lithium Ion	*
	Nominal Capacity (kWh)	1	HOMER 2022
	Nominal Voltage (V)	3.7	HOMER 2022
	Nominal Capacity (Ah)	282.7	HOMER 2022
	Roundtrip Efficiency (%)	92	HOMER 2022
	Maximum Charge Current (A)	270	HOMER 2022
	Maximum Discharge Current (A)	810	HOMER 2022
	Capacity Ratio	1	HOMER 2022
	Rate Constant (1/hr)	74.3	HOMER 2022
	Capital Cost ($/kWh)	(See Storage Cost)	Ramasamy et. al. 2022
	O&M ($/kWh-yr.)	10	Mongird et. al. 2020
	String Size	1	*
	Float Life (yrs.)	15	HOMER 2022
	Throughput (kWh)	2,742	HOMER 2022
	Size (Num. Batteries)	~	Homer Optimized
	Minimum State of Charge (%)	20	Calculations done with 80% DOD
System Converter			
	Rated Capacity (kW)	~	HOMER Optimized
	Capital Cost ($)	0.1	Cost Included with PV Array
	Lifetime (yrs.)	25	Project Lifetime
	Inverter Efficiency (%)	95	HOMER 2022
	Rectifier Efficiency (%)	95	HOMER 2022
	Relative Capacity (%)	100	HOMER 2022
Grid Connection			
	REMC (Block Rates)		
	Energy Charge (¢/kWh)	8.05*	*Averaged Based off Load Data
	Demand Rate ($/kW)	6.59	
	Sellback Rate (¢/kWh)	3.89	
	REMC (On/Off Peak Hours)		
	On-Peak Rates (¢/kWh)	9.12	
	Off-Peak Rates (¢/kWh)	4.73	
	Sellback Rate (¢/kWh)	3.89	
	Demand Rate On-Peak ($/kW)	15.78	
	Demand Rate Off-Peak ($/kW)	5	
	Energy United		
	Energy Charge (¢/kWh)	4.7*	*Averaged Based off Load Data
	Demand Rate ($/kW)	6.25	
	Sellback Rate (¢/kWh)	4.23	

HOMER Cost Table Input for Battery Module				
Capacity (kWh)	Capital ($)	Capital w/ Incentives ($)	Capital Deduct. & Incentives ($)	O&M ($/Year)
1	1265	664	531	10
29	36685	19260	15408	290
30	31830	16711	13369	300
99	105039	55145	44116	990
100	81700	55703	44562	1000
1200	732000	384300	307440	12000

HOMER Cost Table Input for PV Module				
Capacity (kW)	Capital ($)	Capital w/ Incentives ($)	Capital Deduct. & Incentives ($)	O&M ($/Year)
1	3600	1890	1512	17
10	36000	18900	15120	170
11	34100	17902.5	14322	187
19	58900	30922.5	24738	323
20	54000	28350	22680	340
49	132300	69457.5	55566	833
50	130000	68250	54600	850
99	257400	135135	108108	1683
100	220000	115500	92400	1700
249	547800	287595	230076	4233
250	500000	262500	210000	4250
499	998000	523950	419160	8483
500	900000	472500	378000	8500
1000	1800000	945000	756000	17000

APPENDIX B: FEDERAL INCENTIVE COST SAVINGS

System Capital Cost ($)		Ferederal Tax (%)
180000		17.3
		Solar System ITC (%)
Bonus Depreciation (%)	40	30
		Total Credit (%)
Percentage of ITC (%)	85	47.3
Amount of ITC ($)	153000	
Bonus Total ($)	61200	
Accelerated Depreciation (%)	20	
MACRS Total ($)	18360	
Net Impact of Depreciation ($)	13764	
Total Reduced Tax Liability ($)	67764	

System Capital Cost ($)		Ferederal Tax (%)
180000		17.3
		Solar System ITC (%)
Bonus Depreciation (%)	40	30
		Total Credit (%)
Percentage of ITC (%)	=(100-D6/2)	=D6+D4
Amount of ITC ($)	=(C8/100)*B4	
Bonus Total ($)	=C9*(C6/100)	
Accelerated Depreciation (%)	20	
MACRS Total ($)	=(C12/100)*(C9-C10)	
Net Impact of Depreciation ($)	=(D4/100)*(C14+C10)	
Total Reduced Tax Liability ($)	=(B4*(D6/100))+C16	

APPENDIX C: BATTERY MODEL PARAMETERS FOR CYCLE LIFETIME

Depth of Discharge (%)	Cycles to Failure
100	1200
70	3000
55	4500
45	5800
30	11000
Model parameters from data:	1/N = A*DoD^beta
Fitted A:	0.00014423
Fitted beta:	1.7945
Estimated Lifetime throughput (kWh):	8103.3
Degridation Limit (%):	20